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GEOLOGICAL-SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS FOR APPURTENANT STRUCTURES AT GATHRIGHT DAM, VIRGINIA

by

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There are no active faults in the region surrounding Gathright Dam, though a notable earthquake occurred in Giles County about 60 km to the southwest. The Giles County source was interpreted to have a maximum potential of MM IX which attenuates to MM VII at the dam and is the severest event to be expected at that site. Peak horizontal motions at the damsite for a mean plus one standard deviation were interpreted as 130 cm/sec^2 for acceleration, 14 cm/sec for velocity, and 11 sec for bracketed duration equal to or greater than 0.05 G. These values are for use as parameters in selecting or scaling accelerograms and response spectra for use in dynamic analyses. A recommended group of accelerograms are included in the report.

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PREFACE

The US Army Engineer Waterways Experiment Station (WES) was authorized to conduct this study by the US Army Engineer District, Norfolk, on 16 November 1988, under DA Form 2544, No. CE-89-3003.

Dr. E. L. Krinitzsky and Mr. J. B. Dunbar, Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory (GL), WES, performed the investigation and wrote the report. Ms. Marsha Darnell, Information Technology Laboratory, and Mr. Dale Barefoot, EEGD, helped to prepare the illustrations. The project was under the general direction of Dr. Arley G. Franklin, Chief, EEGD, and Dr. William F. Marcuson III, Chief, GL.

COL Larry B. Fulton, EN, was Commander and Director of WES during the preparation of this report. Dr. Robert W. Whalin was Technical Director.

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GEOLOGICAL-SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS FOR APPURTENANT STRUCTURES AT GATHRIGHT DAM, VIRGINIA

PART I: INTRODUCTION

Purpose and Scope

1. The purpose of this investigation is to define the maximum potential for earthquakes at Gathright Dam, Virginia, and to provide time histories for earthquake motions that represent the cyclic shaking that would be felt in the free field on bedrock at the damsite. Ground motions defined by this study are for use in the engineering-seismic evaluation of appurtenant structures at Gathright Dam.

2. The investigation includes both a geological and seismological analysis and consists of the following parts: (a) an examination of the local and regional geology with an evaluation of faulting, (b) a review of the historical seismicity for the area under study, and (c) the determination of the maximum earthquake(s) that will affect Gathright Dam together with the attenuated peak ground motions at the damsite. The maximum earthquake ground motions specified are in accordance with the requirements mandated by ER 1110-2-1806 of 16 May 1983.

Study Area

3. The area covered by this study includes that portion of the southeastern United States in which earthquake activity has the potential to affect Gathright Dam. Gathright Dam is located in Virginia, near the border between Virginia and West Virginia (see Figure 1). The study area is in general limited to the region contained within a circle, with the reservoir formed by Gathright Dam at its center, and having a radius of approximately 100 miles (160 km). The study area includes portions of Virginia and West Virginia and incorporates Giles County, Virginia. Giles County is the site of the second largest historic earthquake in the southeastern United States. The Giles County earthquake occurred in 1897 and was felt over much of the southeastern and eastern parts of the United States.

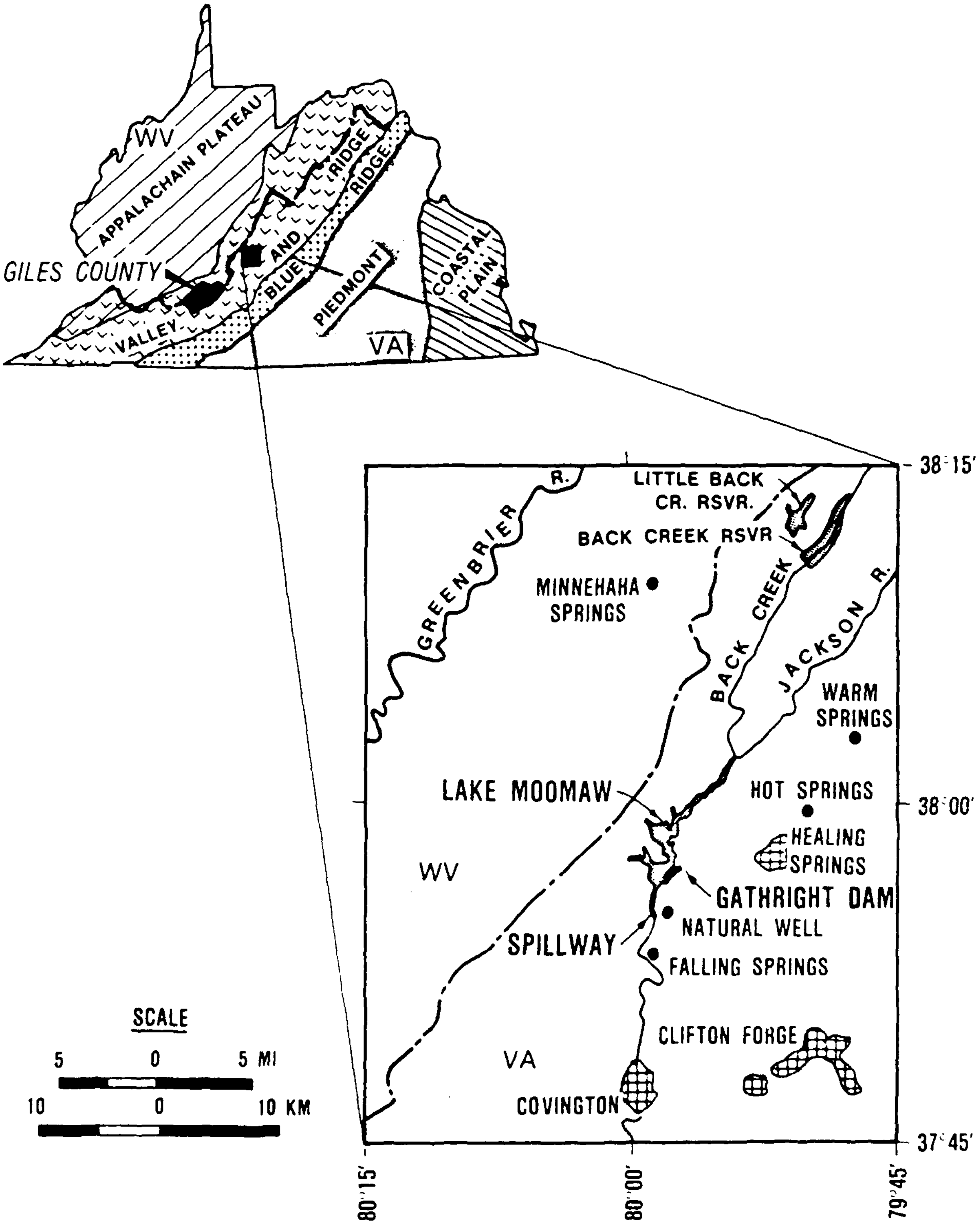

Figure 1. Map showing the location of Gathright Dam and physiographic subdivisions in Virginia and West Virginia

4. Gathright Dam is located on the Jackson River, approximately 10 miles (16 km) upstream from Covington, Virginia. The dam is located in northern Alleghany County and the majority of the reservoir, Lake Moomaw, is located in southern Bath County. Lake Moomaw is approximately 12 miles (19 km) long and ranges from less than 1/4 to 1-1/2 miles (1/2 to 2-1/2 km) in width. Gathright Dam is a rolled rockfill embankment with an impervious compacted earth core and a concrete cut-off wall in the left abutment for seepage control (U.S. Army Corps of Engineers, 1983a). Construction of Gathright Dam was begun in 1967 and was completed in 1980. Gathright dam is a multipurpose dam, providing flood control and recreation. The dam and reservoir are operated by the U.S. Army Corps of Engineers, Norfolk District.

PART II: GEOLOGY

Geologic Setting

5. The study area is situated in the Central Appalachian Mountains, approximately at the junction between the southern and central segments of the Appalachian chain. The Appalachian Mountains are a major physiographic feature that extend through the eastern United States. They begin in Western Alabama and continue into the eastern provinces of Canada. The Appalachian Mountains are dominated by intense folding, with numerous faults, and are composed of a vast variety of sedimentary, metamorphic, and igneous rocks.

6. The Appalachian Mountains are subdivided into geologic provinces based on similar rock types and stratigraphy, structural features, geologic history, and similar topography. The major subdivisions in the Central Appalachians are the Appalachian Plateau, the Valley and Ridge, the Blue Ridge, and the Piedmont Provinces (see Figure 1). Gathright Dam is located in the Valley and Ridge Province, near the Appalachian Plateau boundary.

7. The Valley and Ridge Province is composed of intensely folded and faulted, mostly unmetamorphosed, Paleozoic (600 to 250 million years (m.y.)) age sedimentary rocks. In contrast, the Appalachian Plateau is composed of relatively undeformed Paleozoic sedimentary rocks. Crystalline rocks occur at the surface to the east, in the Blue Ridge and Piedmont provinces. The Blue Ridge Province is composed of thrust-faulted Precambrian (before 600 m.y.) basement (igneous and metamorphic) rocks. The Piedmont Province is composed of highly metamorphosed and folded Paleozoic and possibly Precambrian sedimentary and igneous rocks.

Tectonic History

8. A brief summary of the tectonic history of the southeastern United States is presented below as it aids in understanding the present geology and seismicity of the study area. The geology and structure of the different geologic provinces identifies a complex tectonic history that involve multiple periods of deformation during the past 600 million years. The geologic history includes wide-spread volcanism, metamorphism, and several collisions of the eastern North American continent with other crustal fragments (island

arcs) and the African continent (Cook and others, 1979, 1981, and 1982, Hatcher, 1972 and 1978; Rankin, 1975; Van Der Voo, 1979; and Williams and Hatcher, 1982). The major tectonic features identified in Figure 2 were produced during the Paleozoic as a result of a series of continental collisions. Associated faults shown in Figure 2 are from Price (1986), Calver (1963), Butts (1933), Lowery and others (1971), and Johnson (1977).

9. Williams and Hatcher (1982) proposed a model for the Appalachians as a mosaic of tectonic terrains or <u>suspect terrains</u> that have been accreted to the eastern North American continent because of continental collisions during the Paleozoic. The mechanism of plate tectonics, the movements and interactions of the plates that form the earth's crust, resulted in the opening of a Late Precambrian to Early Paleozoic Iapetus Ocean, the expansion of the Iapetus ocean and associated deposition of sediments into this ocean, and the eventual closure of the Iapetus ocean by the Late Paleozoic. Times of major deformation or mountain building during the Paleozoic are interpreted to correspond to periods when plate collisions have occurred and crustal fragments were added to the leading edge of the ancestral North American continent. Three main periods of deformation are recognized for the Appalachian Mountains. These periods of deformation or mountain building correspond approximately to the Taconic (450 to 500 m.y.), Acadian (350 to 400 m.y.), and Alleghany (250 to 300 m.y.) Orogenies.

10. The style and characteristics of deformation during each tectonic period varied widely along the Appalachian chain and each episode of mountain building affected segments of the Appalachian Mountains differently. Williams and Hatcher (1982) interpret the Valley and Ridge, the Blue Ridge, and the Piedmont Provinces as being suspect terrains that approximately correspond to the Piedmont, Avalon, and Brunswick terrains as shown by Figure 3 (from Wheeler and Bollinger, 1984). Wheeler and Bollinger (1984; also Bollinger and Wheeler, 1983) suggest that <u>suspect terrains</u> are candidates for earthquake source zones and that they may help explain seismicity in the southeastern United States. Causes of seismicity for the southeastern United States will be examined in greater detail in Part III of this report.

11. The three major periods of deformation during the Paleozoic produced wide-spread volcanism, metamorphism, folding, and/or large scale westward transport of numerous vertically stacked thrust sheets. The major period of thrust faulting and folding in the Central and Southern Appalachians

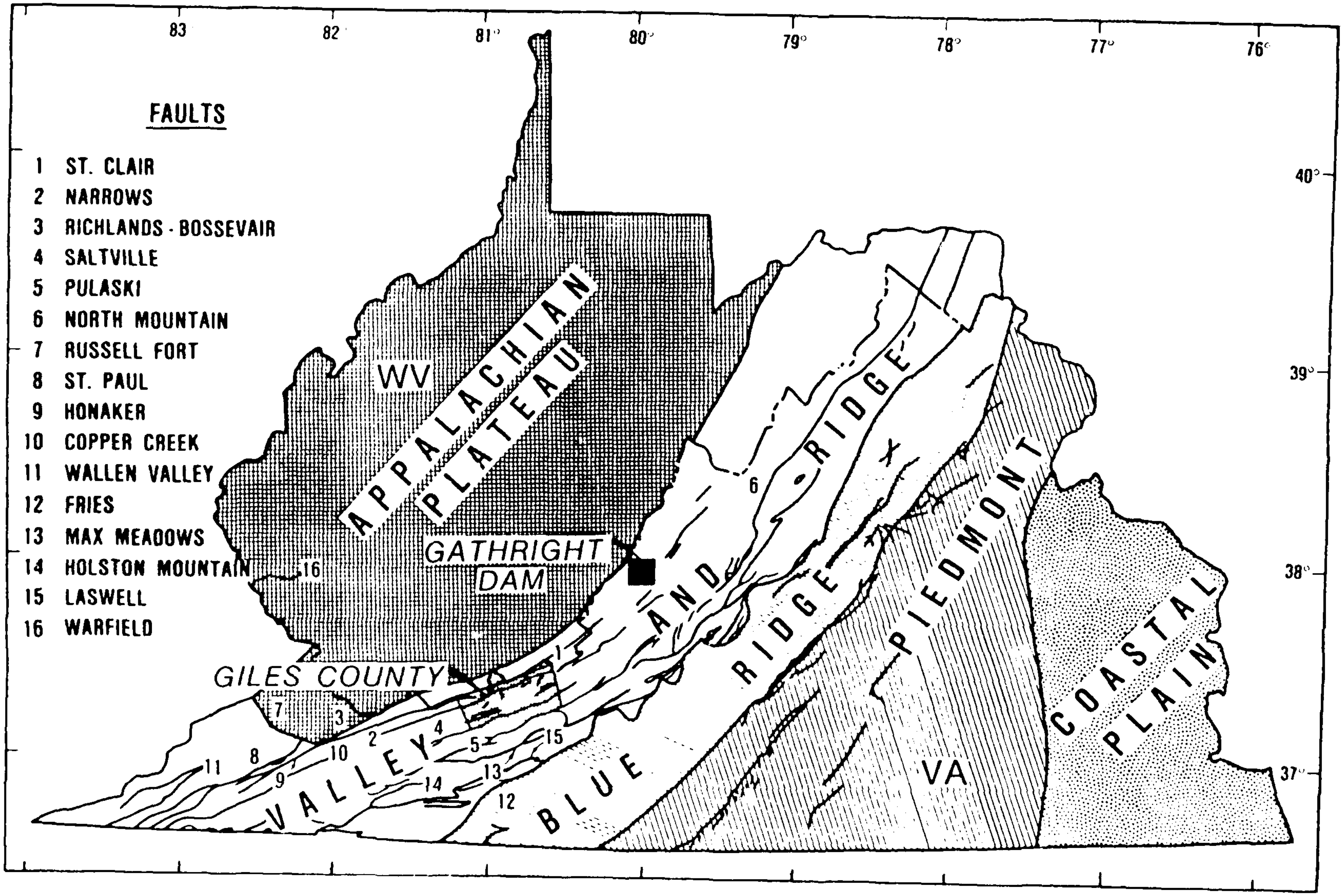

Figure 2. Tectonic map of Virginia and West Virginia showing physiographic subdivisions and the locations of major faults (fault data from Price, 1986; Calver, 1963; Butts, 1933; Lowery and others, 1971; and Johnson, 1977)

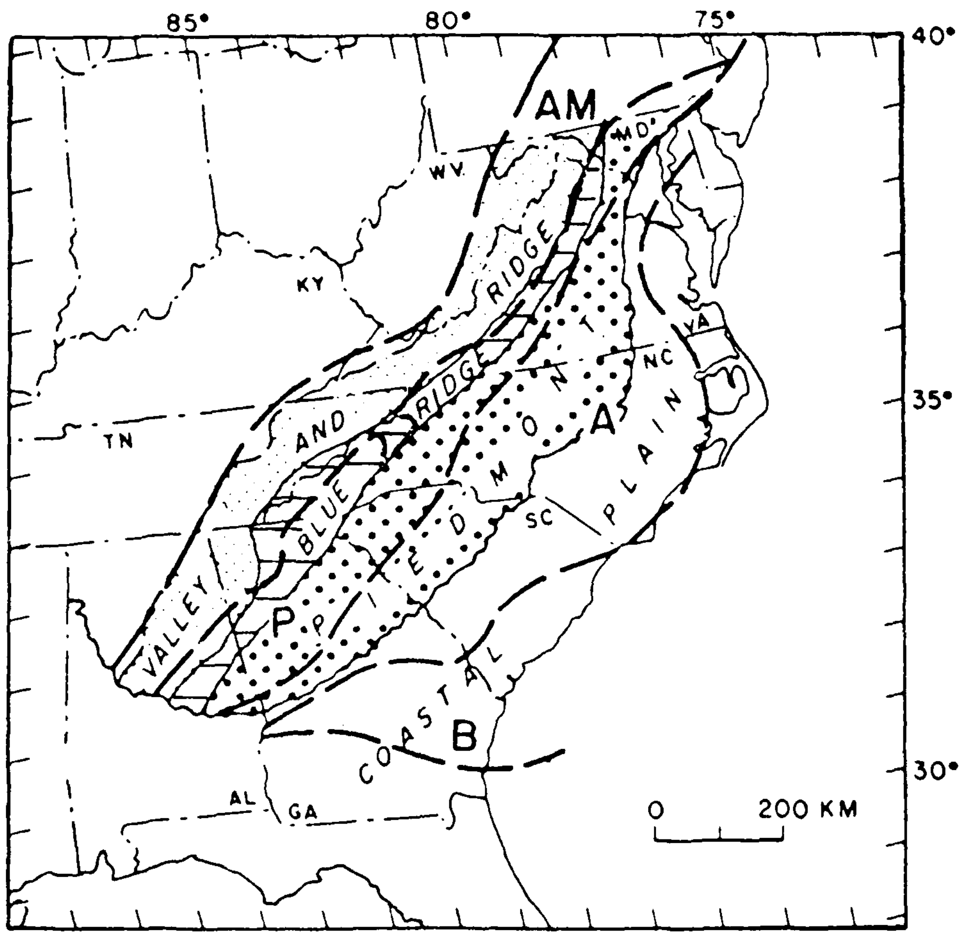

Figure 3. Map showing geologic provinces and suspect terrains in the southeastern United States (from Wheeler and Bollinger, 1984). Provinces: small dots represents Valley and Ridge; stippled represents Blue Ridge; large dots represents Piedmont; and no pattern represents the Coastal Plain. Suspect terrain boundaries are from Williams and Hatcher (1982): Appalachian continental margin (AM), Piedmont (P), Avalon (A), and Brunswick (B) terrains

is interpreted to have occurred during the last collision event, when Africa and North America were joined together (Cook, Brown, and Oliver, 1982; Evans, 1989; Hatcher, 1972; Lowery and others, 1971; and Van der Voo, 1979). Thrust faulting was a primary mechanism for creation of the Central and Southern Appalachian Mountains as indicated by several deep penetrating seismic reflection profiles (Harris, deWitt, and Bayer, 1986; Cook Brown and Oliver, 1981; and Oliver, 1982). Underlying the Valley and Ridge in the Central and Southern Appalachian chain is the interpreted edge of the proto-North American continent. Overlying this ancient continental edge, are the thrust faulted nearshore and marine sediments from the earlier Iapetus Ocean. These thrusted sediments form the underlying geologic section at Gathright Dam. West of the study area in the Appalachian Plateau, major thrust faults are absent; instead, compression was limited to minor folding.

12. The final stage in the tectonic history of the Central Appalachians and the southeastern United States began in the Mesozoic Era (250 to 65 m.y.). Rifting separated North America from Africa and created the modern Atlantic Ocean. The separation of the two land masses represents a change in the style of tectonism from compression to extension. Relaxation of crustal stresses produced the Triassic basins (250 to 210 m.y.), which are bounded by normal faults, and produced the intrusion of numerous cross-cutting mafic dikes throughout the southeast.

13. The Triassic basins have since been filled with sedimentary deposits that were eroded from steep mountains to the east. These basins are presently buried by Cenozoic deposits (65 m.y. to present) beneath the Coastal Plain. Some of these basins are exposed in the Piedmont Province in Virginia (Marine and Siple, 1974). The Triassic mafic dikes are well developed in the southeastern United States and in portions of central and northern Virginia, where they cut across the structural grain of the Appalachians, extending approximately northwest to southeast (King and Beikman, 1976 and Calver, 1963). Basin formation, normal faulting, and dike intrusion are interpreted to have ended by the latter part of the Jurassic Period (210 to 145 m.y. ago).

14. The Cenozoic Era (65 m.y. ago to present) is a period of relative continental stability. The coastal plain was formed during this time from sediments that were eroded from the uplifted Appalachian Mountains and deposited along the continental margin. The glacial advances during the Pleistocene (2 m.y, to 10,000 years) are the last major crustal disturbances

to have occurred in North America. The glaciers did not advance into the Valley and Ridge Province (Flint, 1971).

Regional Geology and Structure

15. A detailed discussion of the geology in the Central Appalachians is beyond the scope of this study. The following discussion will be restricted to describing the fundamental geologic and structural characteristics of the Valley and Ridge Province as they relate to Gathright Dam and to possible sources for earthquakes.

16. The major geological and structural features in Bath and Alleghany Counties are presented in Figure 4A (from Rader and Gathright, 1984) with the individual stratigraphic units identified in Figure 4B (from Rader and Gathright, 1984). The dam and reservoir are located west of the Warms Springs Anticline. The geology has been mapped as being of Paleozoic age, composed of Ordovician to Mississippian age sediments. Anticlines and synclines are the major structural features in the three county area identified in Figure 4A. This area of Virginia is part of the Western Anticlines (Rader and Gathright, 1984). Because of the intense folding throughout this area, the structure and stratigraphy are highly variable. The sedimentary rocks that comprise the area have been subjected to several periods of deformation, producing multiple fold orientations with plunging anticlinal and synclinal structures.

17. Bath and Highland Counties are both noted for unusual geologic features. These two counties contain the largest concentration of thermal springs in the eastern United States (Bollinger and Gilbert, 1974). These thermal springs are often associated with travertine deposits. The locations of hot springs in close proximity to Lake Moomaw and Gathright Dam are identified in Figure 1 (note the town locations). In addition, Highland County contains Eocene age (58 to 37 m.y.) volcanic intrusions, the youngest known igneous rocks in the eastern United States (Dennison and Johnson, 1971; and Kettren, 1971). Dennison and Johnson (1971) have proposed that a cooling igneous body in the subsurface is responsible for the hot springs and once was the source for the igneous intrusions in Highland County. The existence of the igneous intrusion has yet to be proven. Studies by Costain and others (1976 and 1978) do not support the existence of the cooling intrusion; instead, they suggest an alternative hypothesis of deep circulation of surface

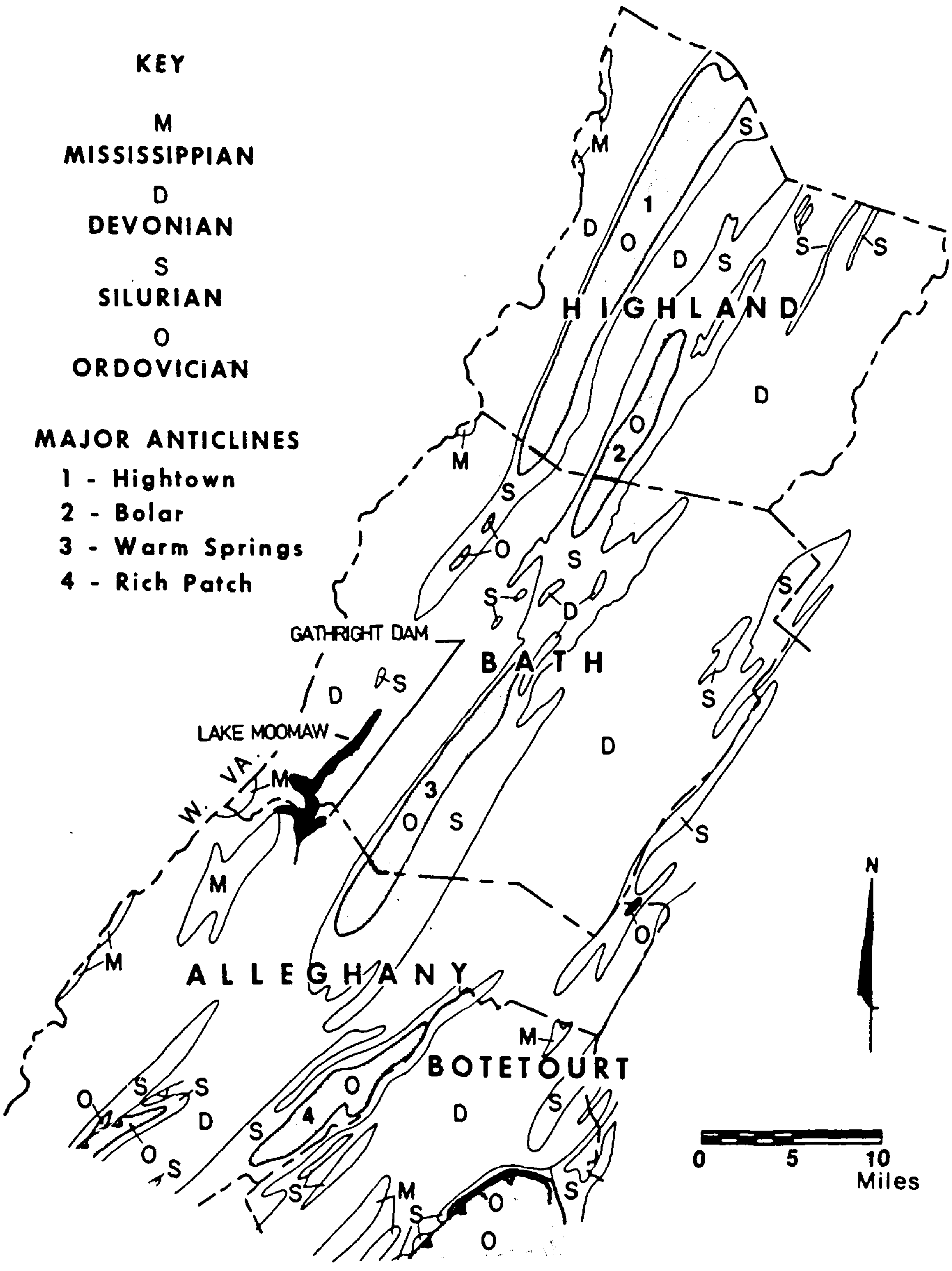

Figure 4A. Generalized geologic map of the Western Anticlines, Virginia; Alleghany, Bath, and Highland Counties (from Rader and Gathright, 1984)

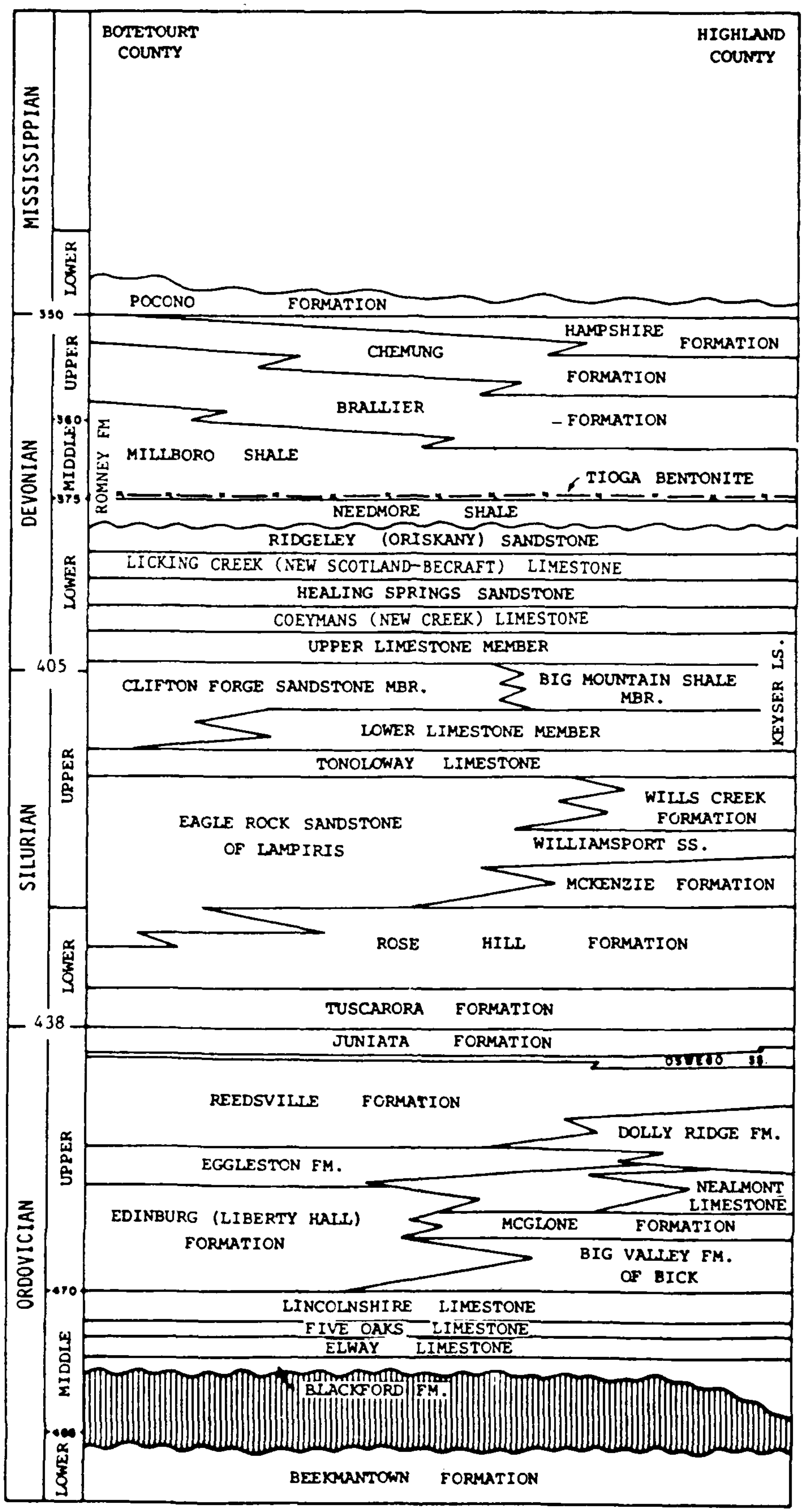

Figure 4B. Stratigraphic units in the Western Anticlines region and at Gathright Damsite (from Rader and Gathright, 1984) water on a normal geothermal gradient by way of existing fractures and faults.

18. The major structures in the Western Anticlines area are related to the compressional events that occurred during the Paleozoic when major thrust faulting and folding are interpreted to have occurred. A generalized subsurface section of the Western Anticlines area, approximately along the Alleghany and Bath County line (see Figure 4A), is presented in Figure 5 (modified from Kulander and Dean, 1978).[1] The structural interpretations shown in Figure 5 are based on detailed gravity and magnetic surveys along the Alleghany Plateau and portions of the Valley and Ridge Province near the Warm Springs Anticline. The Warm Springs Anticline is interpreted to be a major stratigraphic flexure that is part of and related to a series of deep seated thrust faults that sole at depth into a master decollement surface above the Precambrian surface.

19. The local stratigraphy and structure along the Valley and Ridge and Appalachian Plateau boundary will vary with location along the boundary, but the overall mechanism of compressional folding and thrust faulting is common along the entire length for both the southern and central segments of the Appalachian Mountain chain. However; the major linear faults so characteristic of the Southern Appalachians (see Figure 2) are not continuous into the Central Appalachians. The presence of thrust faults at the surface diminishes in the central segment as compared to the southern segment. The presence of major thrust faults in the subsurface is well noted for the central segment (Evans, 1989; Wilson, 1989; Kulander and Dean, 1978; and Dean and Kulander, 1972). Further to the west in the Appalachian Plateau region, the effects of major thrust faulting, common in the Valley and Ridge, the Blue Ridge, and the Piedmont Provinces, are negligible. Instead, Paleozoic compression in the sedimentary cover is expressed by minor folding that eventually diminishes and merges with the relatively flat-lying depositional sequences of the central continent. The deformation of the sedimentary cover in the central Appalachians and in the project area is interpreted as being one of thin skinned tectonism, deformation of the upper crust without active involvement of the underlying crystalline basement rocks (Rodgers, 1971 and

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[1]The cross-section in Figure 5 is modified from the original northwest to southeast cross-section K - K' by Butts (1933), located approximately 1.5 miles south of the damsite.

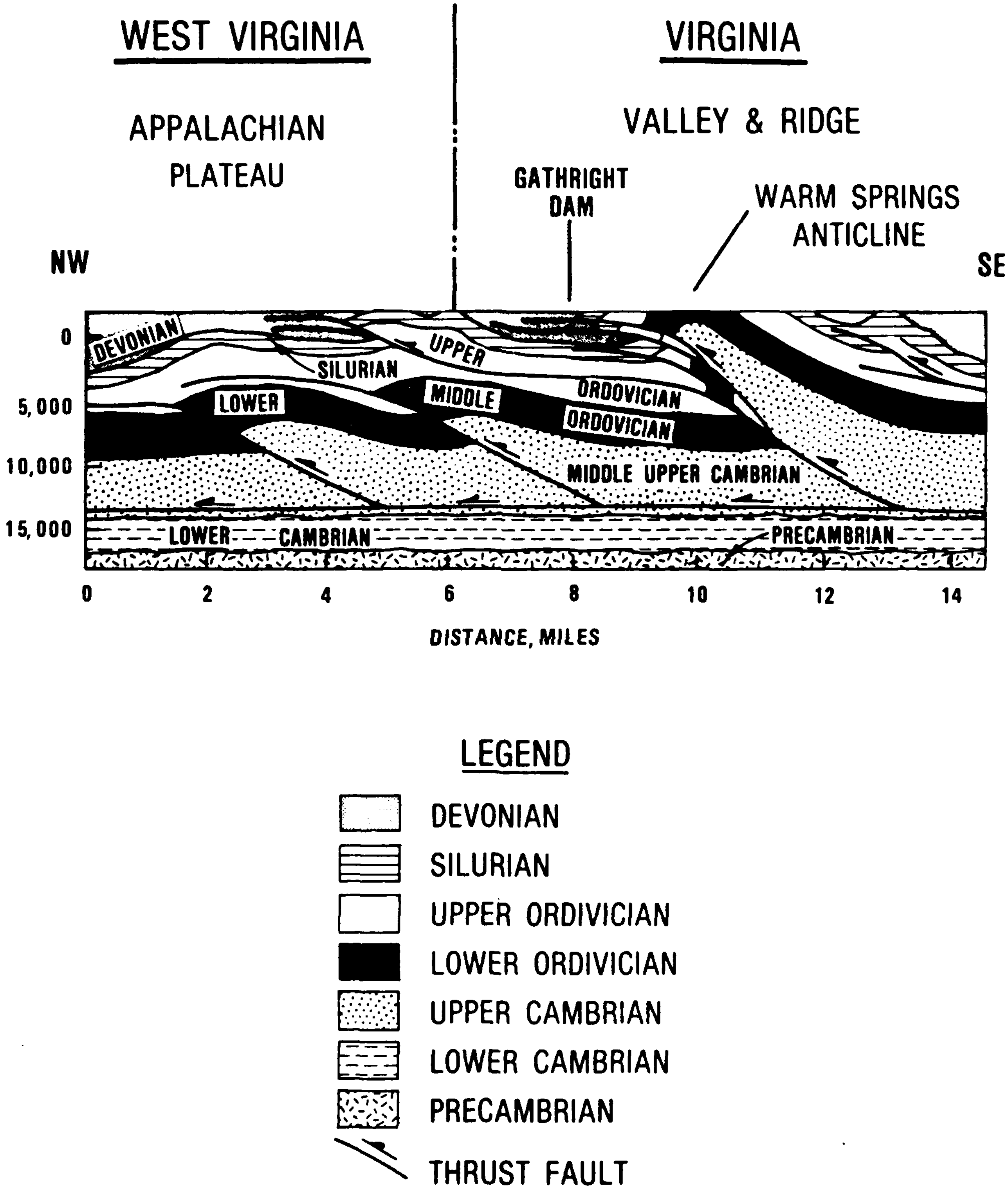


Figure 5. Generalized subsurface structure of Western Valley and Ridge Province near vicinity of Alleghany and Bath County line, Virginia. Subsurface structure interpreted from detailed gravity and magnetic data (from Kulander and Dean, 1978; cross-section location and geology modified from cross-section K-K' by Butts, 1933)

Gwinn, 1964).

General Site Geology and Structure

20. General information concerning the site geology and the structural features in the project area are summarized below and were obtained from various design memoranda and foundation reports (U.S. Army Corps of Engineers, 1966, 1967, 1969, 1976, 1983a, and 1983b). The primary geologic units and structural features underlying Gathright Dam and Lake Moomaw are identified in Figure 6 (from U.S. Army Corps of Engineers, 1983b).

21. Gathright Dam and Lake Moomaw are underlain by Silurian (438 to 408 m.y.) and Devonian (408 to 350 m.y.) sedimentary rocks that have been folded and faulted. The major structural features in the dam and reservoir area are folds, faults, and joints. As previously noted, the intense folding during the Paleozoic produced anticlinal and synclinal structures. Bolar Mountain, Coles Mountain, Morris Hill, and Hoover Ridge are anticlines. Gathright Dam is located in a narrow gorge which the Jackson River has cut between Bolar and Coles Mountains. The dam is located a short distance upstream from the axis of the Morris Hill anticline. Lake Moomaw is contained within a syncline between the surrounding anticlinal structures. Detailed information on the site geology and important structural features are presented in Appendix A. Included in Appendix A is a geologic cross-section from beneath the dam that shows the orientation and distribution of the various rock units.

Determination of Active and Capable Faults

Definition of Active and Capable Fault

22. Earthquakes are produced when strain energy is suddenly released in the form of movements along faults. The identification and recognition of active faults are important in determining the earthquake potential for an area. An _active fault_ is defined by the U.S. Army Corps of Engineers (1983c) as a fault which has moved during the recent geologic past (Quaternary) and, consequently may move again. However, an active fault may or may not be capable of producing earthquakes. An active fault is judged _capable_ of producing earthquakes if it is shown to exhibit one or more of the following

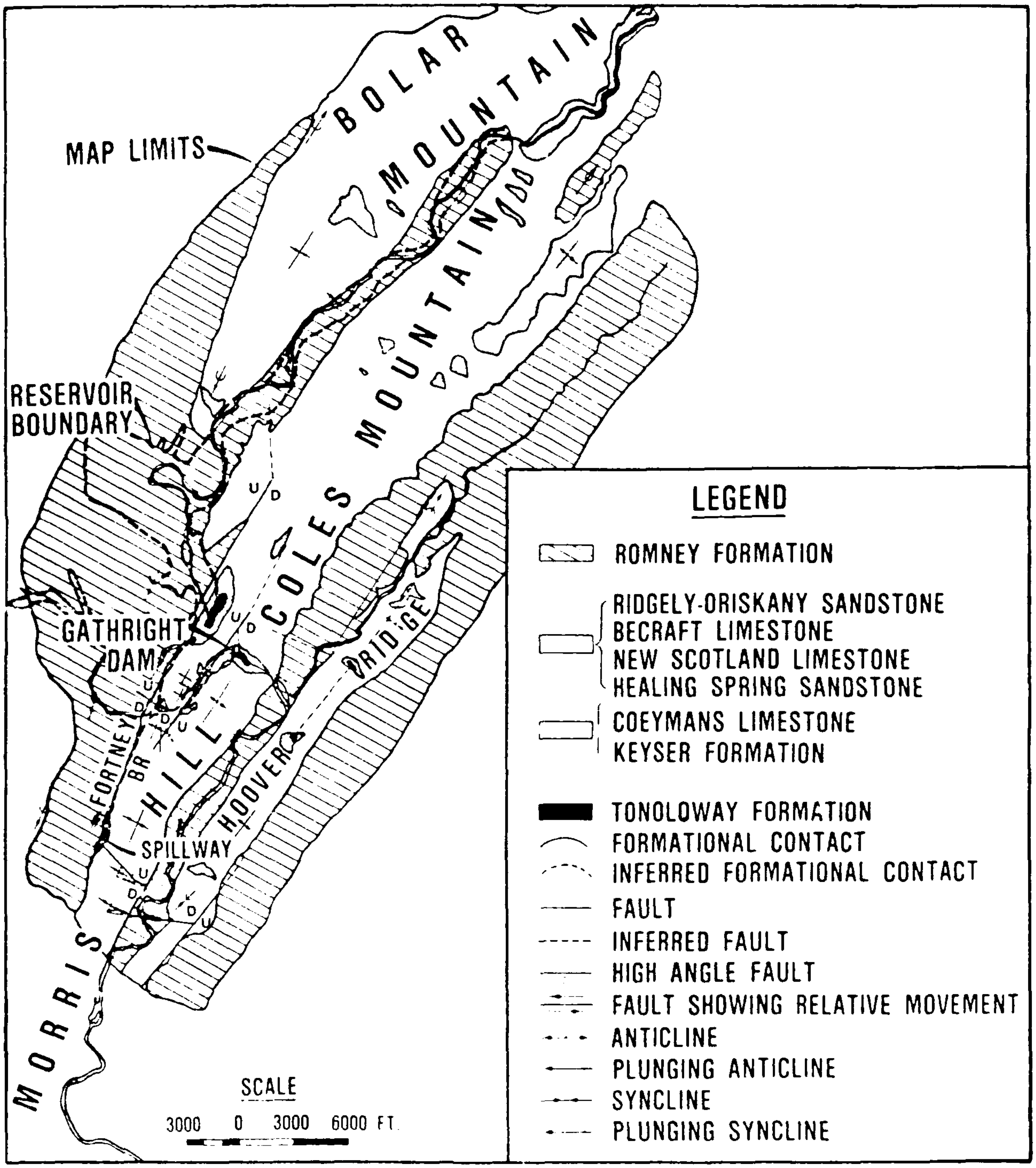


Figure 6. Geology and structure at Gathright Dam and vicinity (from U.S. Army Corps of Engineers, 1983b; Plate II-3). Detailed descriptions of the individual rock units are presented in Appendix A

characteristics:

a. Movement at or near the ground surface at least once during the past 35,000 years.

b. Macroseismicity ($M \geq 3.5$) instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.

c. A structural relationship to a capable fault such that movement on one fault could be reasonably expected to cause movement on the other.

d. Established patterns of microseismicity that define a fault and historic macroseismicity that can reasonably be associated with that fault.

23. In summary, a fault that is active and capable of producing earthquakes must show either geologic and/or seismic evidence of its activity.

Geologic Evidence

24. Numerous geologic studies have been conducted in the central Appalachian region to identify lineaments and possible Post-Paleozoic fault activity (White, 1952; Mixon and Newell, 1977; Dames and Moore, 1977; Reynolds, 1979; Geiser, 1978; Wheeler, 1980; Rader and Gathright, 1984; and Southworth, 1986a and 1986b). These studies are mostly of a general or reconnaissance nature that describe major lithologic aspects of the different tectonic events, significant structural characteristics of ancient tectonism, interpretations of basement structure, or structural characteristics that are related to mineral and petroleum exploration. For the most part, these studies do not identify known Cenozoic age faults or possible earthquake sources at or near Gathright Dam.

25. One study that reports a possible Tertiary age fault near Gathright Dam is by White (1952). Faulting was identified in a road cut on U.S. Highway 60 near Clifton Forge. The road cut is approximately 1 mile due east of the junction between U.S. Highways 220 and 60, approximately 12 miles (19 km) southeast from Gathright Dam. The fault is described by White (1952) as being vertical. It displaces a surface gravel horizon that was fluvially deposited and an underlying shale bed. The fault strike is N 25° W, or transverse to the strike of the central Appalachian Mountain chain. White indicates that the fault is of tectonic origin, based on geomorphic evidence, and he assumed it to be Tertiary in age. Other examples of normal and reverse Cenozoic

faulting are cited by White for several other locations in Virginia and North Carolina. He concludes that many more such minor faults may be present in the southeast. To date, there are no proven Holocene (less than 10,000 years) faults identified in the literature for the southeastern United States.

26. The U.S. Army Corps of Engineers, Norfolk District, conducted a detailed evaluation of faulting as part of the design and construction of Gathright Dam. As part of the evaluation process, the Norfolk District conducted an extensive review of the literature and performed an in-depth geological analysis of the impoundment area in 1973. The geological analysis was conducted by the Raytheon Company under the direction of the Office, Chief of Engineers. The analysis by Raytheon used color aerial photography and high resolution classified black and white imagery.

27. The faults and lineaments that were identified by the Norfolk/Raytheon study were mapped on approximately 1:24,000 scale base maps and these features were then evaluated in the field by a geologist. The mapped faults in the Gathright Dam impoundment area and vicinity are shown in Figure 6. The final report that describes the work performed and results obtained from this study on faulting was classified. There are presently no copies of this report (U.S. Army Corps of Engineers, 1973) available as it was destroyed for security reasons. However, results of this detailed study have been summarized in two later Corps reports (U.S. Army Corps of Engineers, 1976 and 1983b). It was concluded by the Norfolk District, based on their in-depth studies, that there were no active and capable faults in the project area.

28. The following activities were performed as part of this study to identify and evaluate faults near Gathright Dam and to determine whether any of these faults are active and capable of producing earthquakes.

a. An extensive review of the literature was conducted to evaluate the more recent geologic studies for evidence of tectonism, seismicity, and the presence of active faults in the southeastern United States.

b. Aerial photography (black and white 1:24,000, black and white 1:20,000, and color infrared 1,24,000 scale) were examined to identify faults and linears at Gathright Dam and the surrounding vicinity.

c. Obtain and review technical information and interpretations from government and university geologists and seismologists who have knowledge about the geology and seismicity of the study area.

d. Review and evaluate the historic record of seismicity in order to establish causative relations with known faults. A review and analysis of the seismic history and seismicity for the study area is presented in the next section of this report.

29. There is no evidence in the surface geology or the seismic history that identifies faults capable of producing earthquakes at or near Gathright Dam. It is concluded after evaluating the above information that there are no identifiable active or capable faults at or near Gathright Dam.

PART III: SEISMICITY

Relation Between Seismicity and Geology

30. Geophysical studies are useful in identifying anomalous geologic structures deep within the subsurface. These structures may indicate areas where tectonic stresses are concentrated and whose potential sources exist for earthquakes. The sudden release of built-up strain energy from the focusing of tectonic stresses produces earthquakes. Gravity and magnetic surveys are two important types of geophysical studies that help to define geological irregularities or structures in the subsurface where regional tectonic stresses may concentrate.

31. Figure 7 presents the results of a generalized gravity survey for Virginia and West Virginia (modified from Johnson, 1977; and Dean and Kulander, 1987). A gravity map identifies density variations which in turn indicate differences in rock type and thickness. The gravity map closely parallels the trend of the Appalachian Mountains. It defines the general boundaries between the different tectonic provinces by variations in the contour intensity. The boundary between the Valley and Ridge and Blue Ridge provinces is defined by the steep gravity gradient beginning at the Blue Ridge and Valley and Ridge Boundary. To the east of the Valley and Ridge province, the gravity map defines a gravity high that extends to the coastal plain. To the west of the Valley and Ridge province, the gravity map defines a broad gravity low. Gathright Dam is centered over the deepest part of the gravity low.

32. Kulander and Dean (1978) identify the gravity low beneath Gathright Dam as corresponding to the thickest section of crust in the central Appalachians with an estimated thickness of approximately 34 miles (55 km). They indicate that the low beneath the Gathright Dam represents the combination of the sum gravational effect of: a) large crustal thickness and lateral compositional variations in crust and mantle, b) broad basement surface with low relief, and c) tectonically produced density variations in the cover of Paleozoic sedimentary rocks.

33. An aeromagnetic map is presented in Figure 8. The aeromagnetic map identifies areas having a susceptibility or remnant magnetization of sufficient magnitude to produce a measurable distortion in the earth's

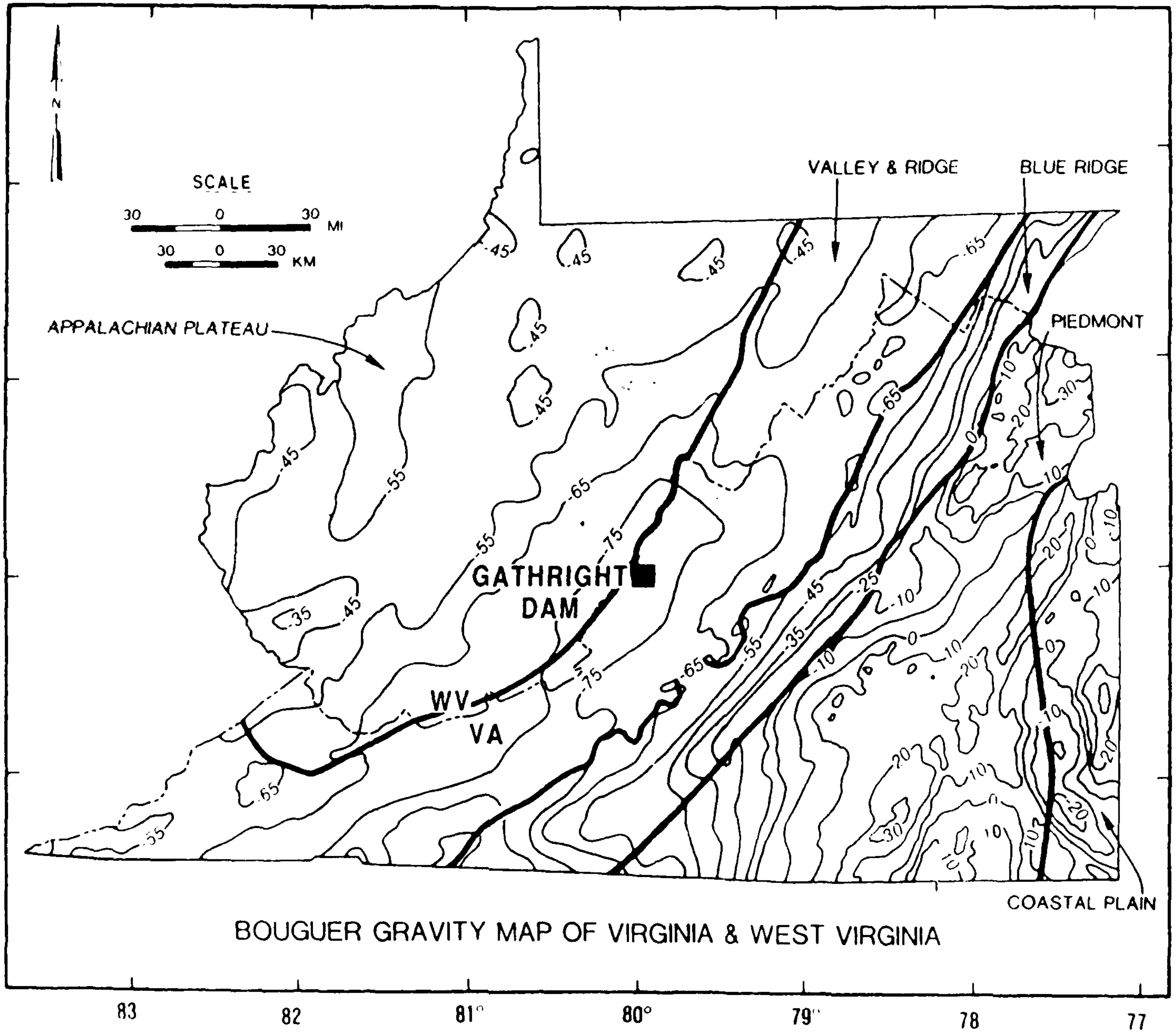


Figure 7. Generalized Bouguer Gravity map of Virginia and West Virginia (from Johnson, 1977; and Dean and Kulander, 1987). Countour interval is in milligals

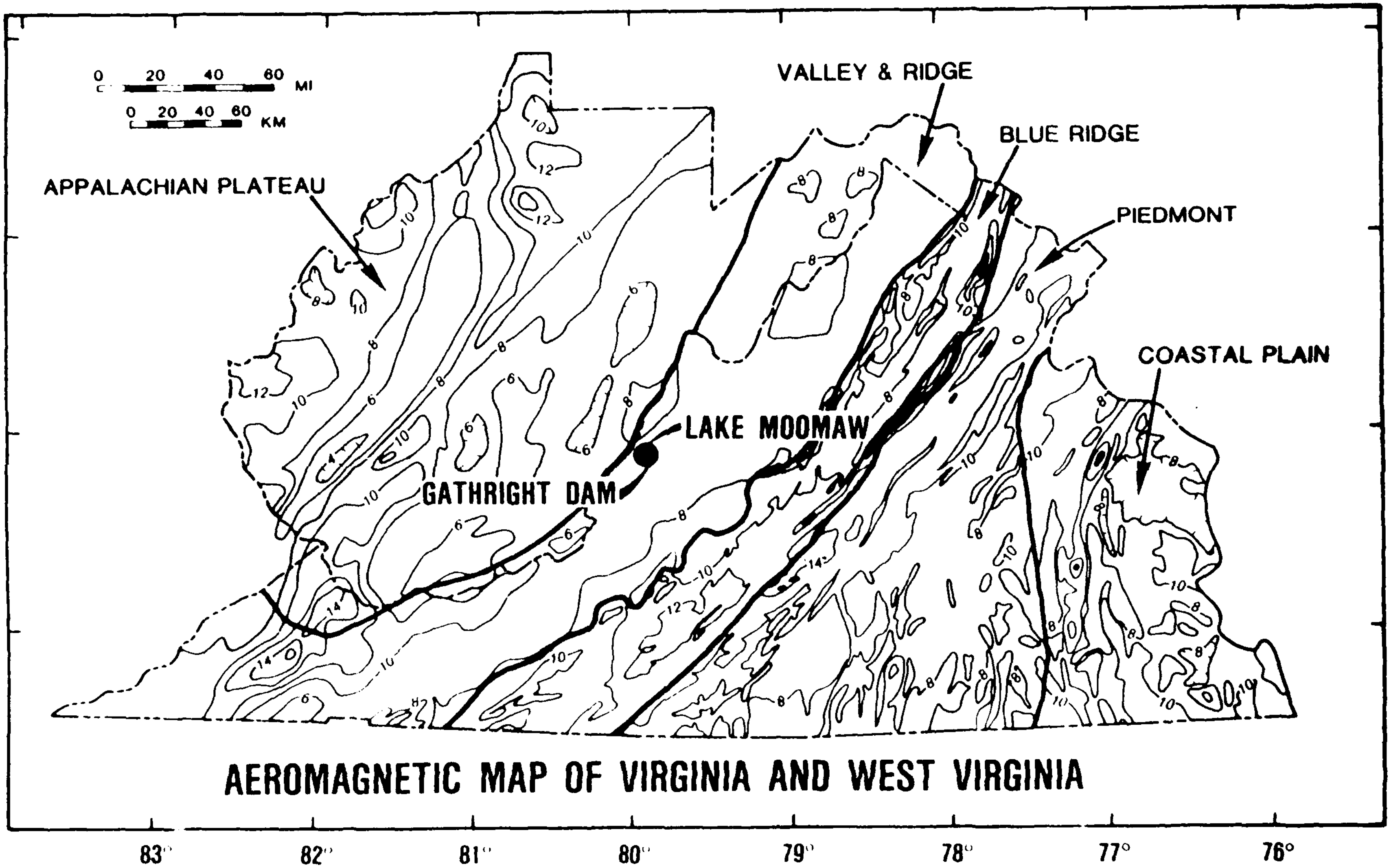


Figure 8. Aeromagnetic map of Virginia and West Virginia; contours are in 100 gammas, contour interval is 200 gammas for contours less than 1000 gammas, and 500 gammas for contours greater than 1000 gammas. Black areas are above 2000 gammas. Values are referenced to an arbitrary datum (after Zeitz and Gilbert, 1980)

magnetic field. Igneous rocks are the primary sources for magnetic minerals that are capable of producing variations in the magnetic field. The aeromagnetic map in general identifies the structural orientation of the central Appalachians. Highest values occur in the Blue Ridge province where the bulk of the igneous rocks are concentrated. Beneath Gathright dam there are no anomalous magnetic structures. The absence of a sharp magnetic anomaly is due to the thick sequence of thrust faulted sedimentary rocks which occur at this location (see Figure 5). The aeromagnetic map in general corroborates the boundaries and other tectonic features identified by the gravity map and indicates an absence of anomalous structures near the damsite.

Causes of Earthquakes

34. Earthquakes are produced when strain energy is suddenly released in the form of movements along faults. Strain energy is derived from regional tectonic stresses which are created by the interactions between the major crustal plates that form the earth's surface. The sudden movement or slippage along fault surfaces produces an elastic rebound. This elastic rebound generates vibrations in the earth's crust and these vibrations are felt as an earthquake. To have a large earthquake requires a large, sudden stress drop and energy release which can only be produced by fault movements that are rooted in the deep crystalline basement rocks.

35. The causes of earthquakes in the southeastern United States and the study area are not well understood as active and capable faults have not been identified to date at the surface. Since active faults have not been identified at surface, there are several theories that have been proposed to explain the causes of earthquakes in the southeastern United States:

a. Focusing of regional stresses at heterogeneities (plutons) or other discordant rock masses in the subsurface and release of this stress by fault movements at depth.

b. Introduction of small-scale magmatic materials into the lower crust, producing stresses, and generating fault movements at depth.

c. Focusing and release of regional stresses along major tectonic discontinuities such as ancient rift zones or transform faults.

d. Regional compression causing activation and slippage along preexisting faults planes such as thrust faults.

e. Regional extension producing movements along fault bounded coastal graben structures (Triassic Basins) or relaxation type movements on existing faults (Barosh, 1981 and 1987; and Armbruster and Seeber, 1981).

f. Localized stress relief along joint planes or other near surface discontinuities (Long, 1988; and Costain, Bollinger, and Speer, 1987). These earthquakes are related to ground water movements and water table fluctuations.

36. The generally accepted view of eastern United States seismicity is that earthquakes occur along pre-existing zones of weakness that are favorably orientated with respect to the present stress field (Bollinger, Ehlers, and Moses, 1987). These pre-existing zones of weakness are interpreted to be ancient faults, paleorift zones, or the intersection points for multiple tectonic features which are located deep in the subsurface. Bollinger, Ehlers, and Moses (1987) indicate the major concentration of earthquakes in the southeastern United States occurs along the Avalon and Piedmont boundary (see Figure 3). Barosh (1987) points out that all of the major seismic areas in the eastern United States lie in or adjacent to the heads of Late Cretaceous-Early Tertiary embayments. In areas where these Cretaceous-Early Tertiary embayment type deposits are absent and historic earthquakes have occurred, Barosh attributes movements along pre-existing zones of weakness, either to sedimentary loading related to these basins or to fault reactivation related to the formation of the Atlantic Ocean and the Gulf of Mexico.

37. The exact cause of seismicity in the eastern United States will be dependent on the site geology and defined by the historic record of seismicity. Explanations a through e in the above list can be interpreted as suggesting that large earthquakes can happen anywhere in the eastern United States or the study area at a location where no historic earthquakes have occurred in the past. To project an earthquake into an area or a zone that has displayed no past seismicity, but is part of a major ancient fault trend or zone, is not considered valid by the present authors unless there is additional evidence for seismicity. A key question that must be asked in such an evaluation as this, is there a relation between the present seismicity and the existing geologic structures? The folding and faulting that have been mapped for the central Appalachians (see Figures 2 and 6) are derived from ancient tectonism which is no longer active today. Present day tectonism is

greatly different from the tectonism which formed these ancient structures. The present seismicity is related to the tectonism and stress fields which are active today.

38. Explanation f above implies a very low upper bound on the maximum earthquake that can occur. The maximum intensity level for this upper bound is believed to be at a level that is below that of concern for engineering. Stress release is near the surface, generally unrelated to any geologic structures except for joints. Some earthquakes are believed to be triggered by ground-water movements through the joints. However, since these earthquakes are shallow and of low energy, a major earthquake is not expected to be generated by this mechanism. In addition, this type of earthquake would be especially apt to occur near reservoirs.

39. Microearthquake monitoring was conducted as part of the construction of the Bath County Pump and Storage facility, a major hydroelectric facility in northern Bath County (approximately 10 miles, 16 km) north of Gathright Dam. The Bath County Pump and Storage project included the construction of two large storage reservoirs (see Figures 1 and 9 for location of Back Creek and Little Back Creek Reservoirs). Microearthquake monitoring was discontinued after several years following construction of the hydroelectric facility as there was no significant earthquake activity associated with the filling of the reservoirs or the daily discharge and filling of the two reservoirs (Bollinger, personnel communication). Information on microearthquake monitoring in the project area and at the Bath County hydroelectric facility is presented in a later section of this report. It is concluded that earthquakes from "hydroseismic" sources will not produce large earthquakes in this region that would adversely affect engineered structures.

40. In summary, the maximum earthquake potential is a function of the present day tectonism. It must be assumed that the largest earthquakes that can occur in the study area are defined by the seismic history and/or by the presence of active faults. These two considerations will control the selection process for the maximum earthquake that is specified.

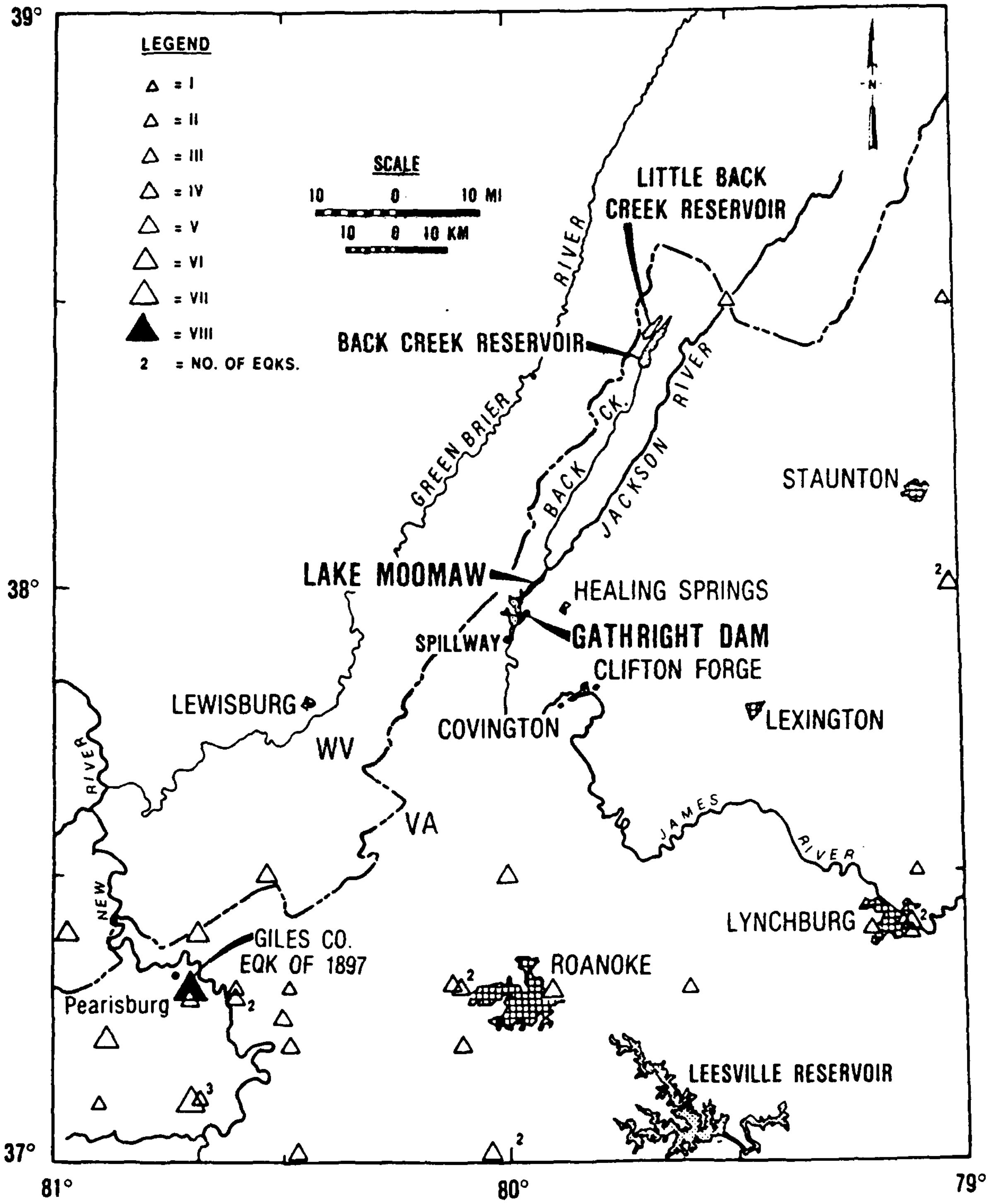


Figure 9. Distribution of historic earthquakes; earthquake data is from Habermann (1989)

Distribution of Historic Earthquakes

41. The distribution of historic earthquakes in the study area is presented in Figure 9. Earthquakes are shown according to the Modified Mercalli Intensity (MMI) scale. The catalogue of historic earthquakes from which Figure 9 was prepared is contained in Appendix B. The catalogue is derived from the Earthquake Data Base maintained by the National Geophysical Data Center, National Atmospheric and Oceanic Administration, Boulder, Colorado (from Habermann, 1989). The list of historic earthquakes is arranged by date and time (Universal or Greenwich Time) and includes coordinate location of the epicenter, earthquake magnitude (m_b, M_L, and M_S), MMI, and focal depth. A glossary of terms is included in Appendix C which includes a description of the MMI scale and the different instrumental or magnitude scales that are used.

42. The catalogue in Appendix B contains a listing of 46 events between the years 1801 and 1986, a history that spans 185 years. The vast majority of earthquakes are less than MMI IV. Only four earthquakes are larger than MMI V. The largest earthquake in the catalogue is MMI VIII. The distribution of historic earthquakes is as follows: 2 earthquakes of MMI I, 5 earthquakes of MMI II, 8 earthquakes of MMI III, 10 earthquakes of MMI IV, 14 earthquake of MMI V, 3 earthquakes of MMI VI, and 1 earthquake of MMI VIII. The MMI VIII earthquake occurred on 31 May 1897 in Giles County, Virginia.

43. Examination of Figure 9 and the State Seismicity Map of Virginia (Reagor, Stover, and Algermissen, 1983) indicates that there is no significant concentration of historic earthquakes in the study area other than at Giles County. The highest concentration of earthquakes in the project area occurs at Giles County. There are no significant historic earthquakes located at or near Gathright Dam. The seismic record indicates a region surrounding Gathright Dam which is classified as aseismic based on the distribution of historic earthquakes.

Microearthquakes

Bath County Microearthquakes

44. Microearthquakes are earthquakes that are too small to be felt (i.e., $M \leq 3$), but are recorded by seismographic instruments.

Microearthquakes are useful for defining areas where tec nic stresses are concentrated. These small earthquakes are helpful in determining focal depths, fault types and their orientations, and aid in estimating rates of earthquake recurrence. Microearthquakes are important in determining if there is a correlation between ancient tectonic structures (i.e., faults, plutons, etc.) and present day seismic activity.

45. Microearthquake monitoring has been conducted in Bath County as part of the construction and seismic evaluation of Virginia Power and Electric Company's new Bath County Pump and Storage Facility, a 2.1 megawatt hydroelectric plant. The Bath County facility, located approximately 10 miles (16 km) north of Gathright Dam, consists of two reservoirs (see Figure 1 for location of Little Back Creek and Back Creek Reservoirs), a powerhouse, and related facilities necessary for generating hydroelectric power. A crustal velocity model was developed for Bath County from construction blasts to accurately define earthquake locations and focal depths. Microearthquake monitoring was conducted for a 3 month period during 1982 with a portable seismographic network and also beginning in 1978 with a permanent 4 station network (Todd, 1982). Todd (1982) concluded that Bath County was aseismic. The three month monitoring program failed to detect any local earthquake activity. Only eleven earthquakes were reported for the long-term monitoring program between 1978 and 1982 and three of these events were to small to locate. The permanent monitoring program was finally discontinued in 1987 as there was very little microearthquake activity. There was no activity associated with the initial filling of the two reservoirs or from the daily filling and emptying of these reservoirs as part of the hydroelectric generating process (Bollinger, personnel communication).

46. The U.S. Army Corps of Engineers, Norfolk District, did not conduct a program to monitor microearthquakes during filling of Lake Moomaw. However, the Bath County Pump and Storage Facility and the Giles County seismic networks were operational during this period and would have detected any anomalous activity associated with the reservoir filling at Gathright Dam. To date, there have been no published reports of any anomalous microseismic activity in Bath County, associated with either Gathright Dam or the Bath County Pump and Storage Facility.

Virginia Microearthquakes

47. Bollinger and others (1986) identify two source areas for

pronounced microearthquake activity in Virginia as shown in Figure 10. The catalogue from which Figure 10 is derived is presented in Appendix D (from Bollinger and others, 1986). The major source of microearthquake activity in the project area occurs in Giles County, the source area for Virginia's largest historic earthquake and the second largest historic earthquake in the southeastern United States. A second zone of microearthquake activity occurs outside of the project area, within Virginia's Piedmont Province, and is known as the Central Virginia seismic zone. Earthquake monitoring in Virginia between 1977 and 1985 indicates that significant differences occur between the two seismic source areas (Bollinger and others, 1986; Bollinger and Wheeler, 1982, 1982a, and 1983; and Munsey, 1984). In Giles County, seismic energy is predominantly released by strike slip movements along a near vertical, tabular zone, approximately 25 miles (40 km) long. Movements are in the crystalline basement rock, approximately 3 to 16 miles (5 to 25 km) deep, and below the basal detachment of the thrust faulted Appalachian sediments (see Appendix D for focal depths). In central Virginia, the release of seismic energy is above the crystalline basement rock, in the thick stack of thrust faulted Appalachian sediments. Movements are from a combination of dip slip and strike slip movements that occur within a circular area approximately 62 miles (100 km) in diameter and 6 miles (10 km) in vertical thickness.

48. A comparison of microearthquake epicentral locations with the epicentral locations for historic earthquakes between the years 1774 to 1977, prior to instrumentation, is shown by Figure 11 (from Bollinger and others, 1986). The source areas for microearthquakes are in close correspondence with the locations of historic earthquakes. The above distribution suggests that earthquake activity in Virginia is confined to "hot spots" which are defined by present day microearthquake activity. Gathright Dam and Lake Moomaw are situated in an area with very little of either category of earthquakes. There has been no significant concentration of historic earthquakes or anomalous microearthquake activity at the damsite. Gathright Dam appears to be located in an aseismic area. The major source for earthquake activity in the project area is located at Giles County.

49. Bollinger and Wheeler (1982) have published a very comprehensive evaluation and analysis of the geology, the historic seismicity, the microearthquake activity, and the tectonism in Giles County. Their interpretation for the causes of earthquake activity at Giles County is that

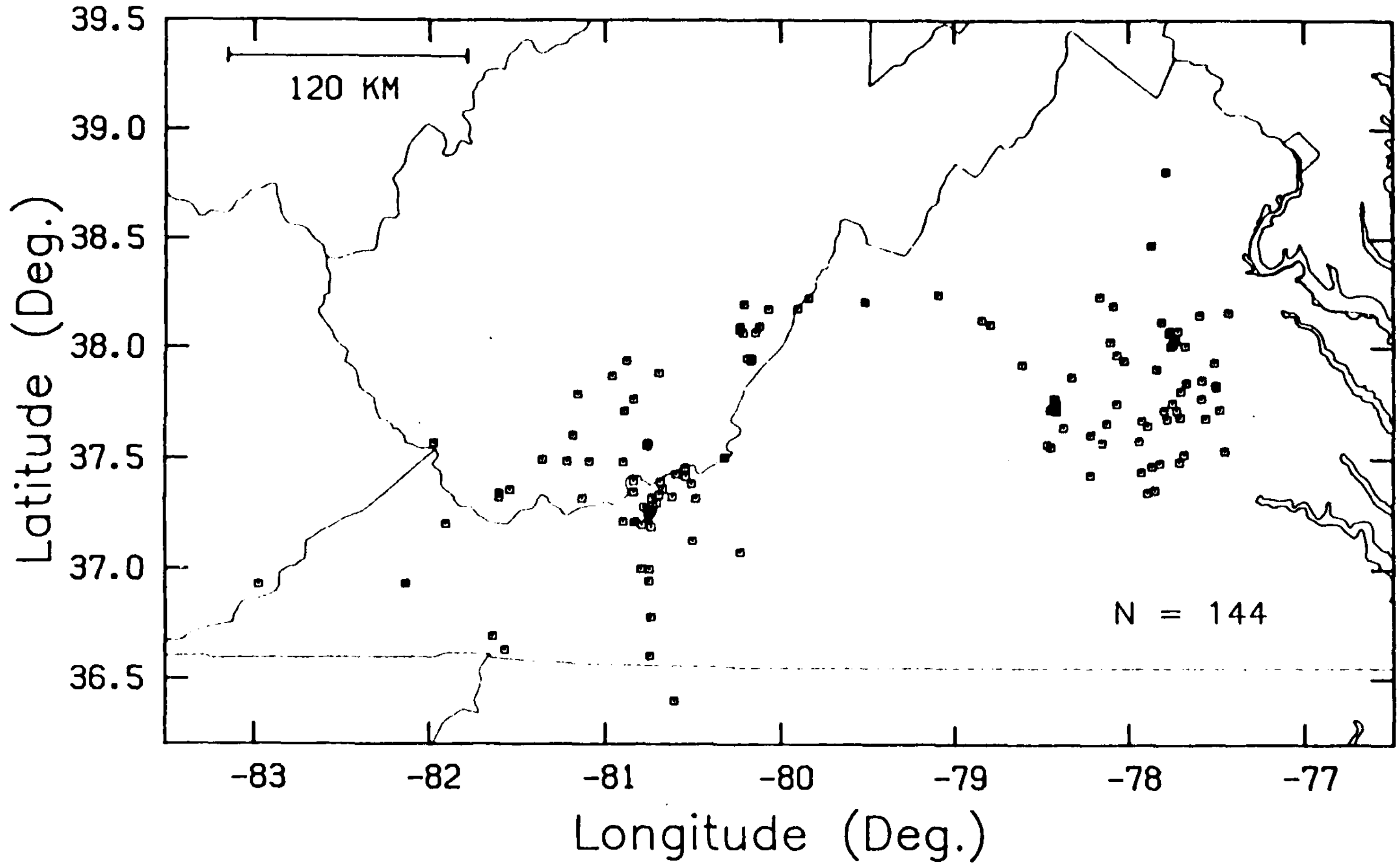


Figure 10. Distribution of instrumentally located earthquakes in Virginia. Earthquakes shown in this figure are presented in Appendix C (from Bollinger and others, 1987)

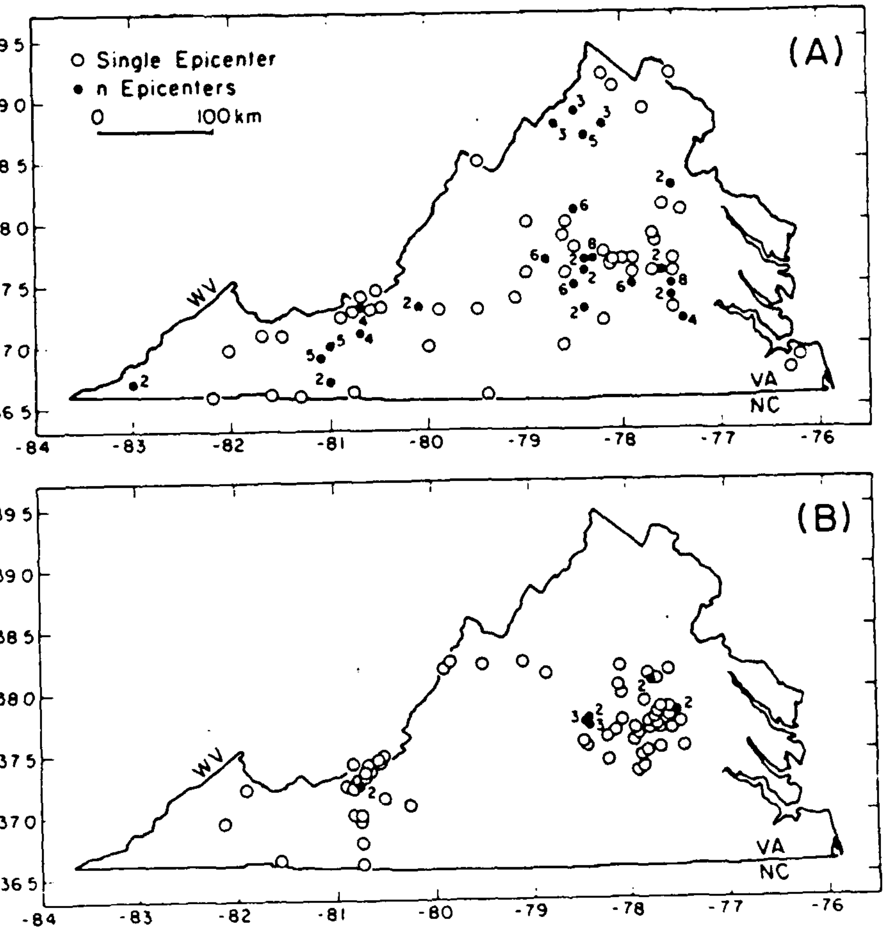


Figure 11. Comparison of historical seismicity in Virginia (Figure 11a) and instrumentally recorded earthquakes (Figure 11b). From Bollinger and others (1986)

earthquakes are produced from compressional reactivation of Iapetan normal faults which occur in the basement in response to the present stress field.

Seismic Source Zones in the Southeastern United States

50. Earthquake source zones are interpreted for the southeastern United States as there are no known active faults. These source zones are based on the record of historic and instrumentally recorded earthquakes. The seismic source zones interpreted for the southeastern United States are shown in Figure 12. The southeastern United States is in general a region of low level seismicity with areas of concentrated earthquake activity. These concentrated areas or zones are called seismic "hot spots" and are potential sources for moderate to major earthquakes.

51. An earthquake zone, as used in this report, is an inclusive area over which a given maximum credible earthquake can occur. This is the largest earthquake that can reasonably be expected to occur. It can be moved anywhere in the zone and is thus a floating earthquake. The earthquake is moved in this manner because causative faults have not been identified. The criteria by which the seismic zones in Figure 12 were developed are as follows:

a. Maximum sizes of earthquakes.

b. Density of earthquakes, using historic seismicity plus microseismic activity where available. A strong occurrence of both together identifies a seismic hotspot.

c. One earthquake will adjust a boundary but cannot create a zone.

d. Zones of greatest activity are generally as small as possible.

e. The maximum intensity of a zone cannot be smaller but may be equal to or greater than the maximum historic earthquake.

f. The zones are source areas. They do not necessarily represent the maximum intensity at every point since attenuations have to be taken into account.

52. The largest earthquake source zones in this portion of the United States are at Charleston, South Carolina and at Giles County. The Charleston area is shown as generating an earthquake of MMI X. An intensity MMI X earthquake occurred at Charleston in 1886. The Giles County area is shown as having the potential to generate an earthquake of MMI IX. The Giles County

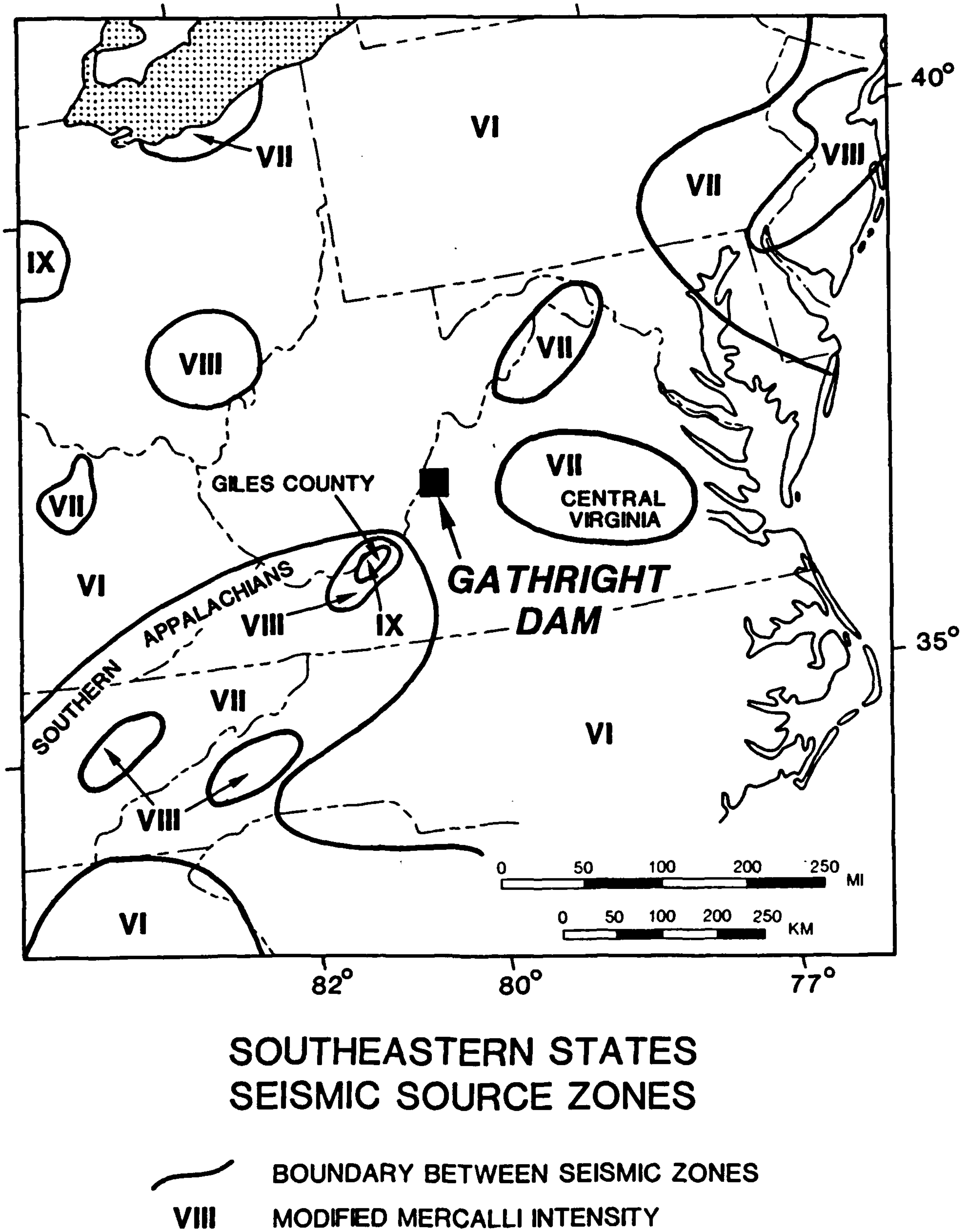


Figure 12. Seismic source zones in the southeastern United States

source area is interpreted as being one intensity level higher than the largest historic earthquake that has occurred. As previously stated, an earthquake of MMI VIII occurred at Giles County in 1897.

53. Examination of Figure 12 shows Gathright Dam as being located in an area experiencing low level seismic activity. The maximum earthquake interpreted for the damsite location is MMI VI. Gathright Dam is bordered on the southwest by the Giles County seismic zone (MMI IX), on the east by the Central Virginia seismic zone (MMI VII), and on the northeast by Northern Virginia seismic zone (MMI VII).

54. The Giles County and the Central Virginia seismic zones are both located within 50 miles (80 km) of Gathright Dam. The Northern Virginia Seismic zone is located more than 50 miles (80 km) from Gathright Dam. Because of its close proximity to Gathright Dam, Giles County is the controlling earthquake source area for Gathright Dam. Consequently, the Central Virginia and Northern Virginia seismic zones are not considered to be as important a seismic hazard as is Giles County.

Maximum Giles County Earthquake

55. An important question that must be addressed is whether the largest possible earthquake has occurred in Giles County. If it hasn't, then what is the largest possible earthquake that is reasonable for this zone? To answer this question, the Waterways Experiment Station engaged Dr. Bollinger, a professor of seismology at the Virginia Polytechnic Institute and State University in Blacksburg, Virginia. Dr. Bollinger is a noted expert on the Giles County Earthquake zone and has published extensively about the characteristics of Giles County seismicity. His report on the maximum earthquake potential for Giles County is presented in Appendix E.

56. Dr. Bollinger interprets the maximum magnitude earthquake at Giles County according to three different techniques: a) adding an increment to the maximum historical earthquake in the zone, b) extrapolating the magnitude recurrence curve for the zone, and c) estimating the maximum magnitude as a function of the interpreted fault plane area that he has projected to occur in the subsurface. The estimate of the fault plane area is determined primarily from information obtained from microearthquakes. Bollinger's estimation of M at the Giles county source by these three methods are 5.9, 6.6, and 7.0,

respectively (Appendix E). Bollinger's extension of the magnitude-recurrence curve to obtain M 7.0 is the least reliable of his estimates since the linearity of the curve for projection to large earthquakes is questionable. An average of the remaining two methods gives M 6.3 which is equivalent to MMI IX. However, an average of all three of Bollinger's methods yields M 6.5 which is also equivalent to MMI IX. Thus, Bollinger's estimates are judged to be consistent with the MMI IX shown in Figure 12.

Earthquake Recurrence

57. A deterministic approach was use in this report to specify earthquake ground motions. A deterministic approach is where a maximum earthquake is interpreted to occur at a fault or seismic source zone and the earthquake is attenuated to the area of interest. The predicted earthquake is specified for the seismic region or zone regardless of the probability of recurrence. The basic assumption is that the engineered structures must be able to withstand the predicted intensity of a maximum credible earthquake whenever it might occur.

58. A recurrence relation is useful for estimating the general return frequency for the maximum event to compare to the operating life of the structure. A recurrence relation is calculated from the seismic record for a given area and the basic Guttenburg-Richter relationship:

$$\log N = a - bM$$

where N is the number of events of magnitude M or greater per unit of time and a and b are constants. A characteristic recurrence period is obtained for a given magnitude from the total number of events for the specified time interval.

59. A recurrence relation for the southeastern United States and selected subdivisions, including Giles County, was developed by Bollinger and others (1989) and is presented in Figures 13a and 13b along with the respective recurrence equations. The historical (intensity based) and instrumental (magnitude based) data sets were combined using relations defined by Sibol, Bollinger, and Birch (1987). The curves are based on the m_{bLg} magnitude scale (see Appendix A for description). The m_{bLg} scale is considered generally equivalent to the m_b scale between m_b 2 to 6.4 (Sibol, Bollinger, and Birch, 1987). The general correspondence between m_b and MMI for the

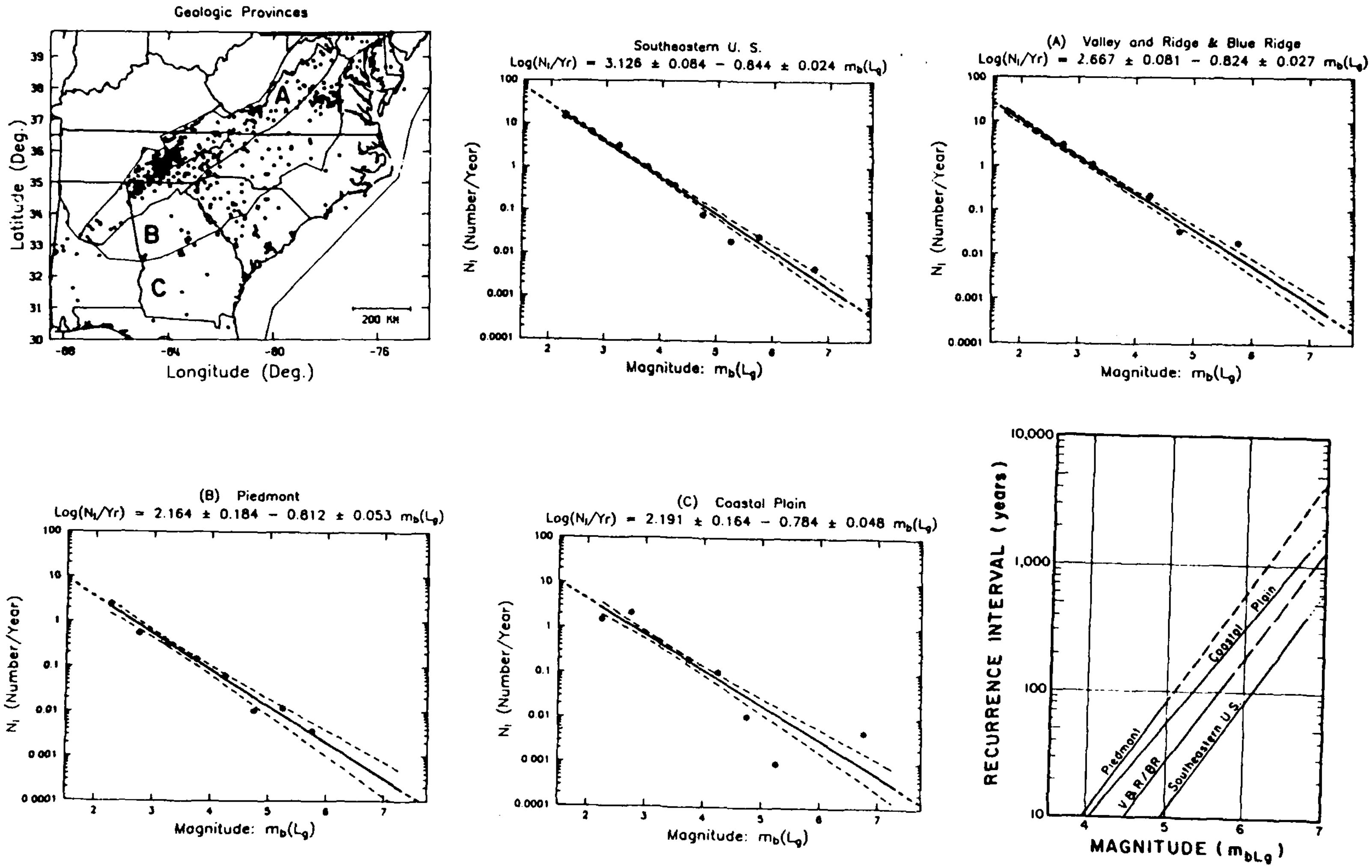


Figure 13a. Recurrence relations for the southeastern United States and its physiographic subdivisions (from Bollinger, Davidson, Sibol, and Birch, 1989)

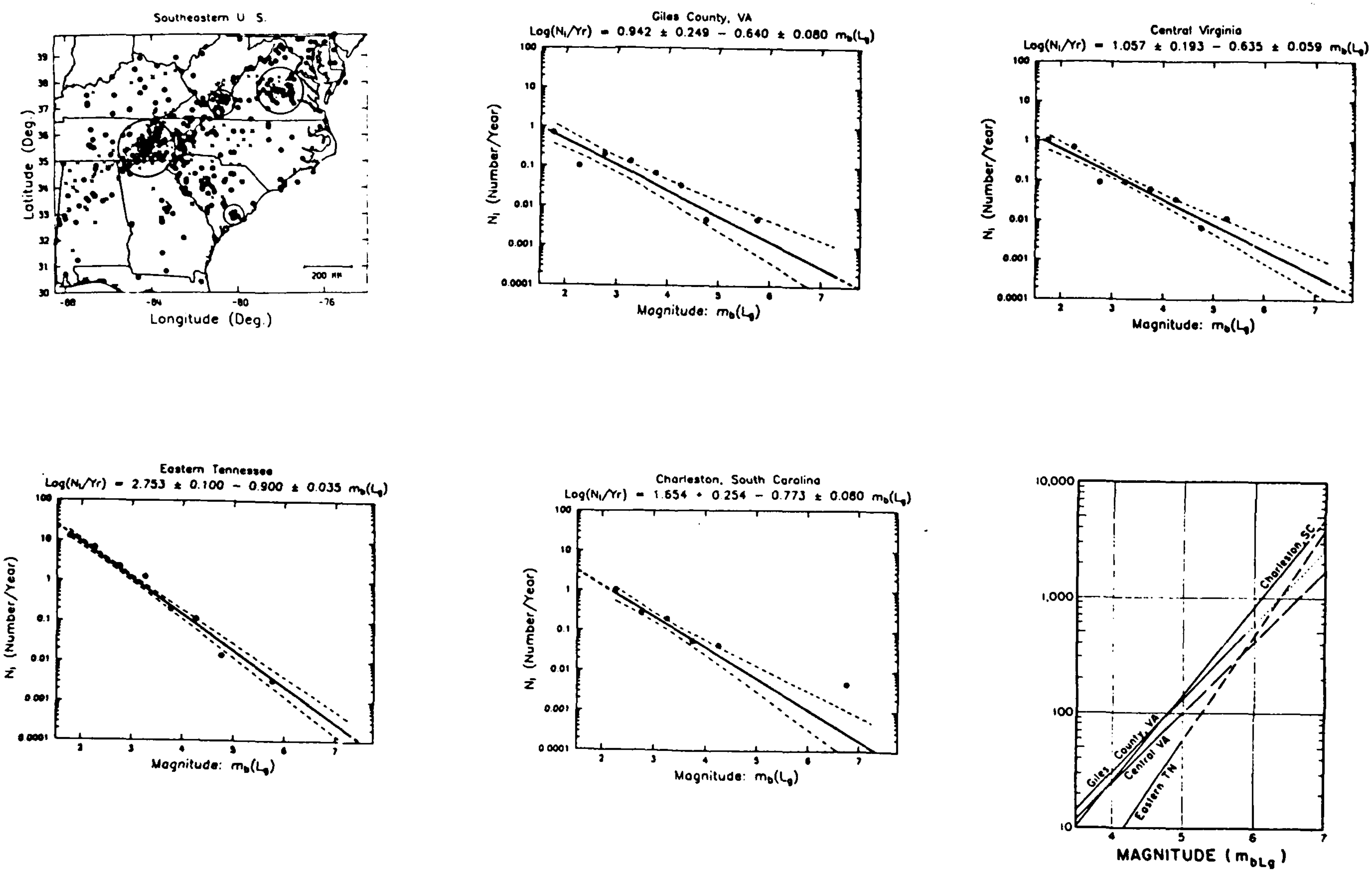


Figure 13b. Recurrence relations for selected seismic hot spots (from Bollinger, Davidson, Sibol, and Birch, 1989)

Eastern United States is presented in Figure 14 (from Sibol, Bollinger, and Birch, 1987).

60. The mean recurrence for an MMI VII earthquake for the southeastern United States region is approximately one every 10 years (see Figure 13a). An MMI VII earthquake is the threshold where damage begins to occur in well built engineering structures (see description of MMI scale, Appendix C). For the Valley and Ridge-Blue Ridge provinces, the mean return period for an MMI VII earthquake is approximately every 30 years. For the Piedmont and the Coastal Plain provinces, the mean recurrence is 80 and 60 years, respectively. The mean recurrence period for an MMI VII earthquake in Giles County is 150 years, for Central Virginia it is 100 years, for Eastern Tennessee it is 80 years, and at Charleston it is 150 years.

61. The mean recurrence estimated for a MMI IX earthquake in Giles County is made by projecting beyond the maximum historic earthquake recorded for the region and also the accuracy range of the data from which the curve is based. The recurrence estimate for the maximum earthquake at Giles County ranges from 310 to 4,200 years at a 95 percent confidence interval (Bollinger and others, 1989). Dr. Bollinger in his report in Appendix E (page E15) states, "...that the interval estimates, at a specified confidence level, rather than point estimates are the preferred manner for utilization of magnitude regression results." However, for purposes of evaluating the seismic potential at Gathright Dam, he estimates a recurrence interval of approximately 1,000 years for the maximum earthquake from the Giles County seismic zone.

62. From the uncertainties in the recurrence equations and the general assumptions that are made in the process of developing recurrence estimates, the entire range of data at each magnitude interval is variable, and may extend over an entire log cycle. Because of this variability and the uncertainty with recurrence or probability estimates, a probabilistic approach is not applicable for specifying maximum earthquake ground motions. The deterministic approach specifies the maximum credible earthquake regardless of the probability of recurrence.

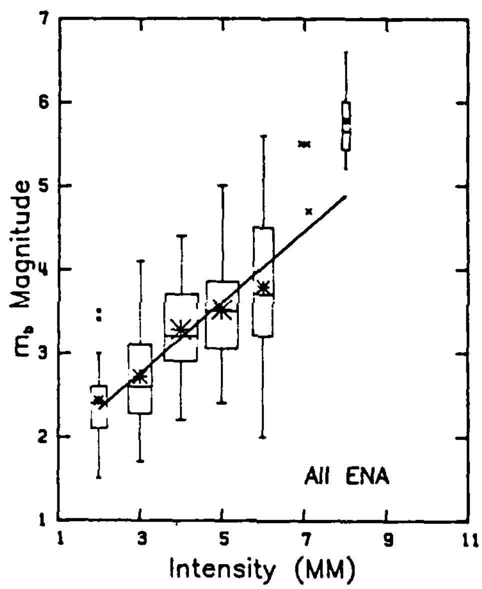


Figure 14. Relationship between m_b magnitude and MM Intensity for eastern North America; range in data is defined by bar length and box plots: mean equals asterisk, 25 and 75 quartiles equals box ends, and median equals center bar (from Sibol, Bollinger, and Birch, 1987)

Felt Earthquakes at Gathright Dam

63. The southeastern region, with the exception of Charleston, South Carolina and Giles County, Virginia, has low level earthquake activity. Table 1 presents a list of MMI VI or greater earthquakes that were judged to have been felt at Gathright Dam. The earthquake list is based on the catalogue in Appendix B for earthquakes within the study boundary and from various published sources (i.e., Coffman, von Hake, and Stover, 1982; Bollinger, 1975 and 1977; and Bollinger and Hooper, 1971; Bollinger and Stover, 1978; Lessing, 1974; and Stearns and Wilson, 1972) for earthquakes centered outside of the study area and which are judged to have been felt at Gathright Dam. The MMI at the source (MMI_0), the distance between the earthquake epicenter and Gathright Dam, and the attenuated MMI at Gathright Dam (MMI_S) are defined for each felt earthquake in Table 1.

64. The attenuation procedure selected for this study is based on the decrease of intensity with distance as determined from curves by Chandra (1979). The attenuation-distance curves are shown in Figure 15 and the curve selected for this study is for the eastern province. The attenuation of MMI is determined by calculating the distance between the earthquake epicenter and the area of interest, selecting this distance on the horizontal axis of the attenuation curve, and then deriving the MMI reduction factor. This reduction factor is then subtracted from the intensity value at the source to arrive at the interpreted felt intensity at the site.

65. The earthquakes in Table 1 span approximately 200 years and identify 15 events that were large enough to have been felt at the damsite. The vast majority of felt earthquakes at Gathright Dam have been less than MMI V. There are five earthquakes in the list that are larger than MMI V, four events are at MMI VI and one event is at MMI VII. There is only one earthquake from these five that originated from within the project boundary. The only large event to have originated from inside the project boundary is the 1897 Giles County earthquake.

66. The 1897 Giles County earthquake was felt at Gathright Dam at MMI VI according to the attenuation distance procedure identified above. However, the isoseismal for the Giles County earthquake shown in Figure 16 (from Bollinger and Hopper, 1971) identifies Gathright Dam as being in the MMI V isoseismal area. According to the list of felt intensities for the towns

Table 1. Felt Earthquakes at Gathright Dam

Inside Study Area Boundary (see Appendix B)

Date	N. Lat	W. Long	Location	Distance miles (km)		MM Io[1]	MM Is[2]
3 May 1897	37.1	80.7	Dublin, VA	72	(116)	VII	V
31 May 1897	37.3	80.7	Giles County (Pearisburg, VA)	60	(97)	VIII	VI
5 Feb 1898	37.0	80.7	Pulaski, VA	80	(129)	VI	IV
11 Nov 1975	37.2	80.9	White Gate, VA	73	(117)	VI	IV
23 Apr 1959	37.4	80.7	Elgood, WV	68	(109)	VI	IV
20 Nov 1969	37.4	81.0	Elgood, WV	68	(109)	V-VI	III-IV
Outside Study Area Boundary							
21 Feb 1774	37.3	77.4	Petersburg, VA	145	(233)	VII	IV
22 Dec 1875	37.6	77.4	Richmond, VA	140	(225)	VII	IV
23 Dec 1875	37 7	78.3	Arvona, VA	90	(145)	VII	V
10 Oct 1885	37.7	78.8	Noorwood, VA	65	(105)	VI	IV
26 Dec 1929	38.1	78.5	Charlottes-ville, VA	79	(127)	VI	IV
31 Aug 1886	32.9	80.0	Charleston, SC	360	(579)	X	II-III[3]
16 Dec 1811	36.6	89.6	New Madrid, MO	650	(1046)	XI-XII	VI[4]
16 Dec 1811	36.6	89.6	New Madrid, MO	650	(1046)	XI-XII	VI
23 Jan 1812	36.6	89.6	New Madrid, MO	650	(1046)	XI-XII	VI
7 Feb 1812	36.6	89.6	New Madrid, MO	650	(1046)	XI-XII	VII[4]

1. Modified Mercalli Intensity at source or origin

2. Modified Mercalli Intensity attenuated to site

3. see Figure 18 (from Bollinger, 1977)

4. see Figure 17 (from Stearns and Wilson, 1972)

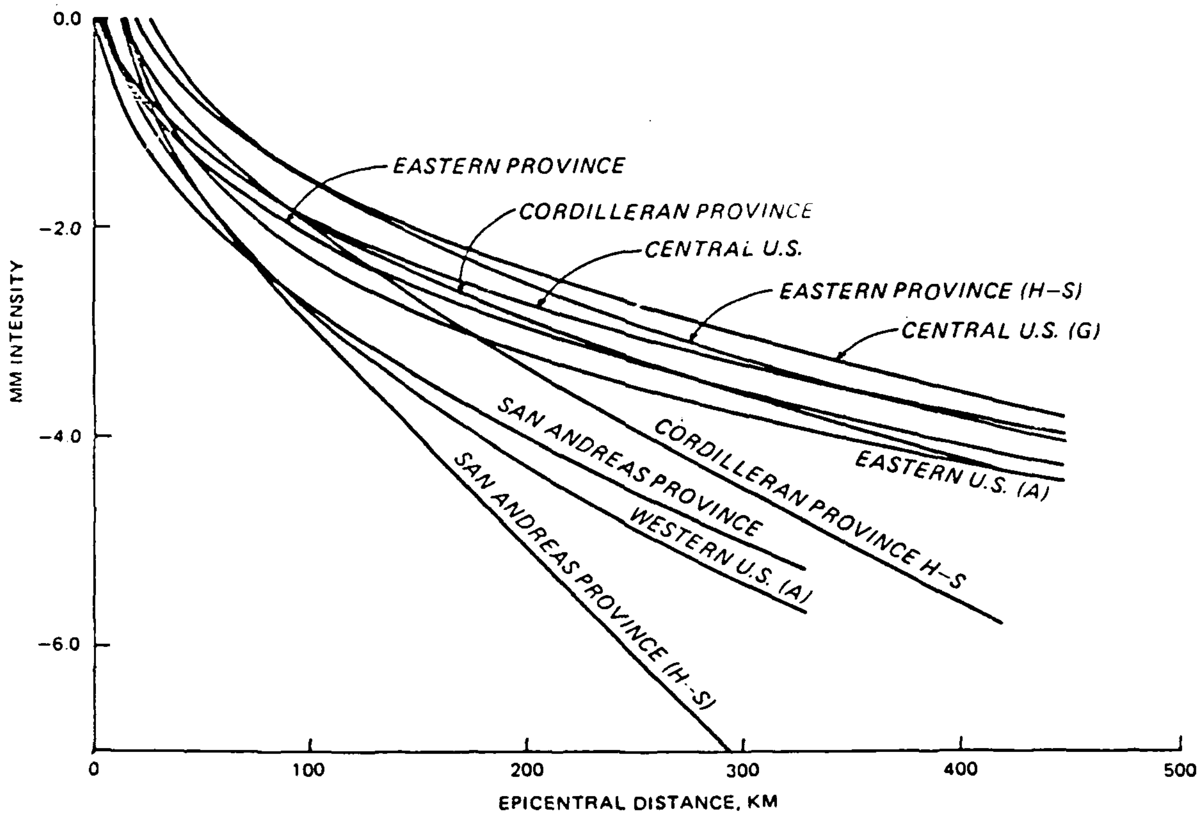


Figure 15. Attenuation of MM Intensity with distance: A = Anderson, G = Gupta, H-S = Howell and Schultz (from Chandra, 1979)

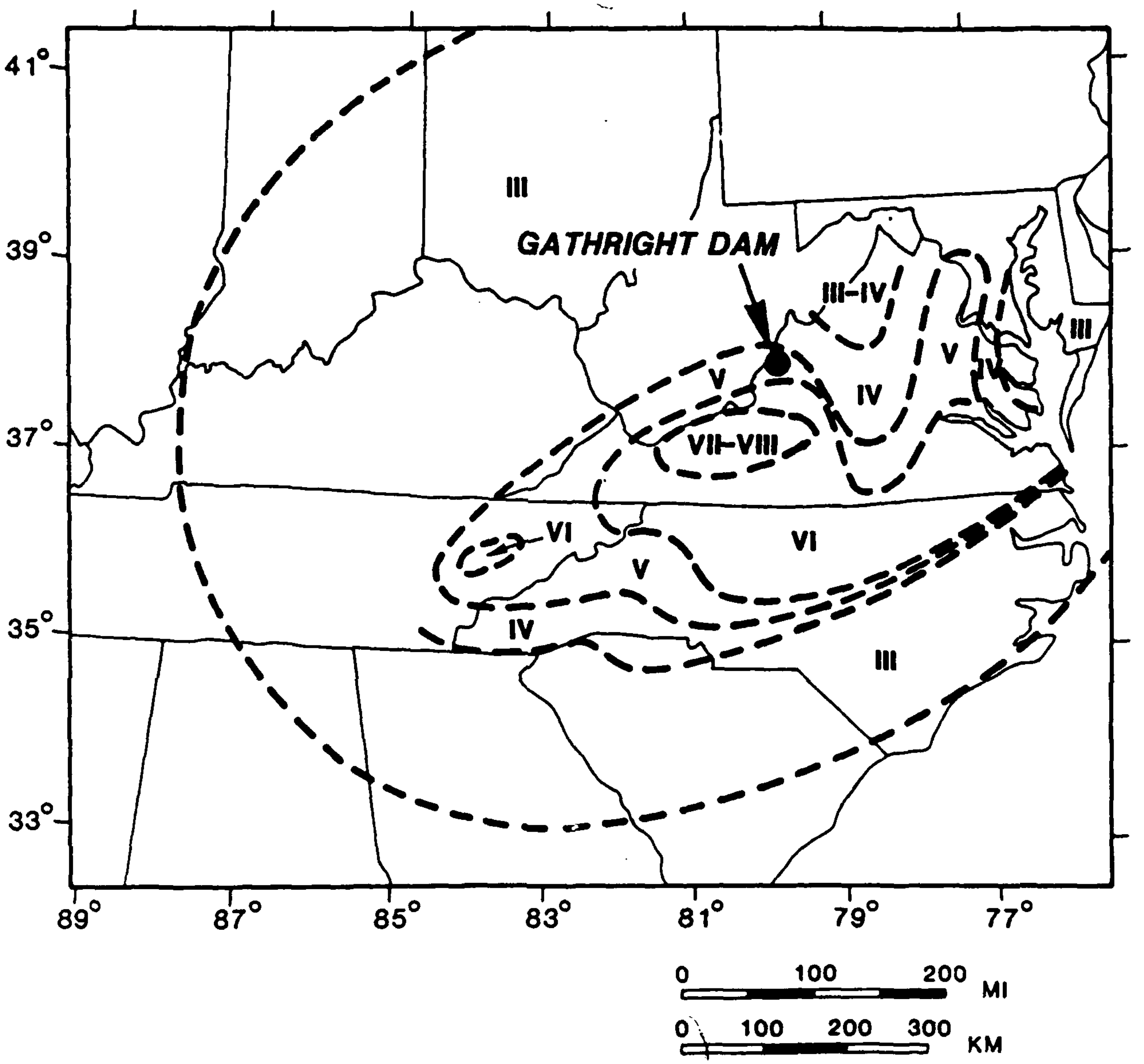


Figure 16. Isoseismal for the 1897 Giles County earthquake (from Bollinger and Hopper, 1971)

nearest Gathright Dam (from Bollinger and Stover, 1978), the area surrounding the damsite experienced effects corresponding to MMI V.

67. The remaining four earthquakes identified in Table 1 which are larger than MMI V originated from the New Madrid seismic zone. The New Madrid region in Missouri is the source for the four largest historic earthquakes to have occurred in North America. Four MMI XII earthquakes occurred in 1811 and 1812 at New Madrid (Street and Nuttli, 1984). It is judged that the maximum historic earthquake shaking at Gathright Dam was experienced during these New Madrid events. Stearns and Wilson (1972) identify the Gathright damsite as being located within the MMI VII isoseismal as shown by Figure 17, a composite isoseismal for the New Madrid earthquakes of 1811 and 1812. Stearns and Wilson define the maximum earthquake shaking at the damsite to have occurred on 7 February 1812. The remaining New Madrid earthquakes are identified by Stearns and Wilson and Street and Nuttli (1984) as being in the MMI VI range.

68. The 1886 Charleston, South Carolina, earthquake produced MMI II to III effects in the Gathright Dam area as shown by the isoseismal in Figure 18 (from Bollinger, 1977). Bollinger and Gilbert (1974) identify the region which encompasses the II-III isoseismal, including the Gathright damsite, as being in an earthquake "shadow zone," with the intensities in the zone less than the surrounding area. The shadow zone is part of an area that has been defined as having low heat flow, a high concentration of thermal springs, great crustal thickness, the presence of Tertiary age volcanic intrusives north of Gathright Dam, located at the transition zone between the central and southern Appalachians, and generally experiencing low level microseismicity activity (Bollinger and Gilbert, 1974). The overall significance of these various characteristics is yet unknown. They suggest that Gathright Dam is located in an area that experiences low level seismicity because of the underlying geology and has crustal attenuation characteristics that are greater than the surrounding area.

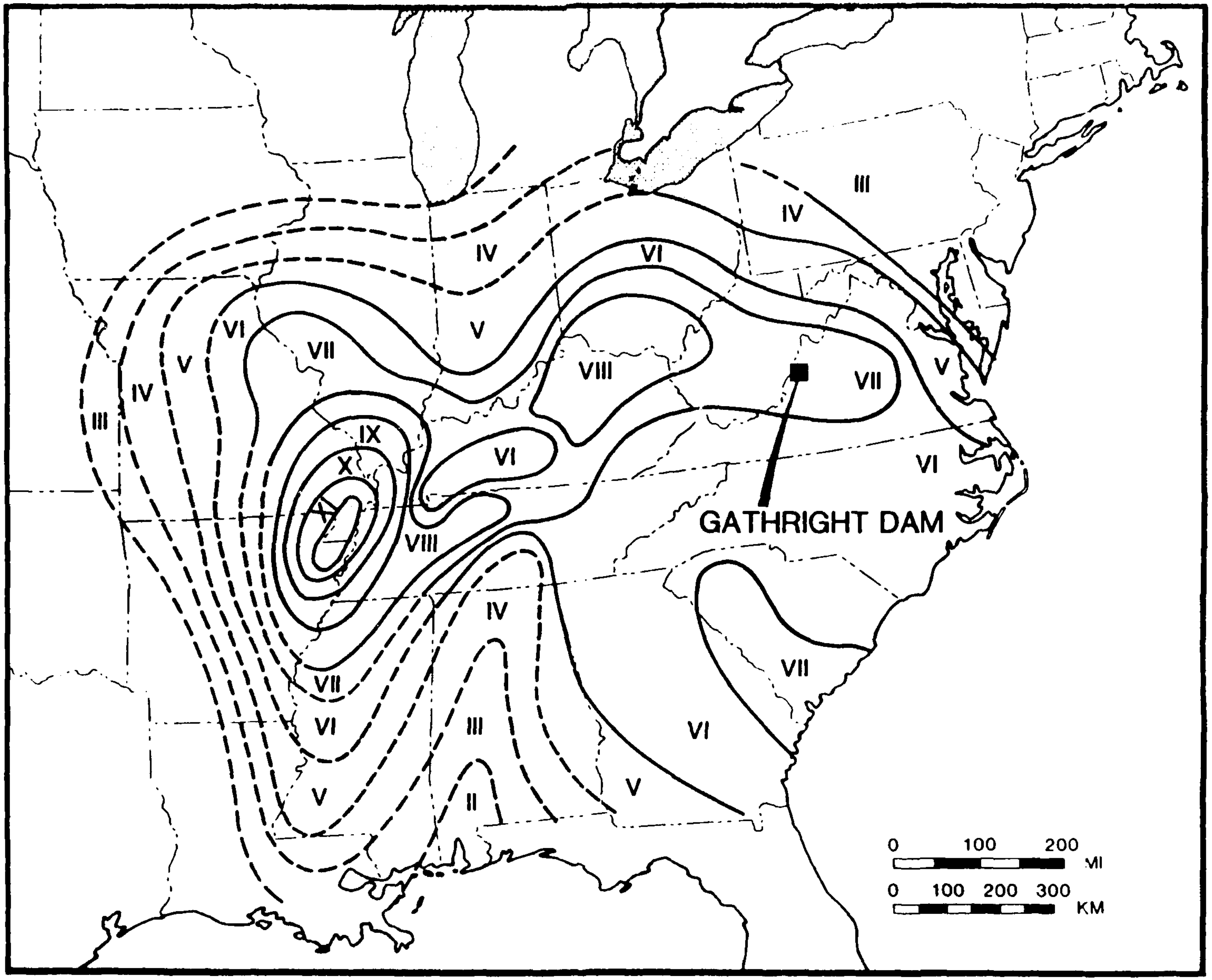


Figure 17. Composite isoseismal for the 1811 - 1812 New Madrid, Missouri, Earthquakes (from Stearns and Wilson, 1972)

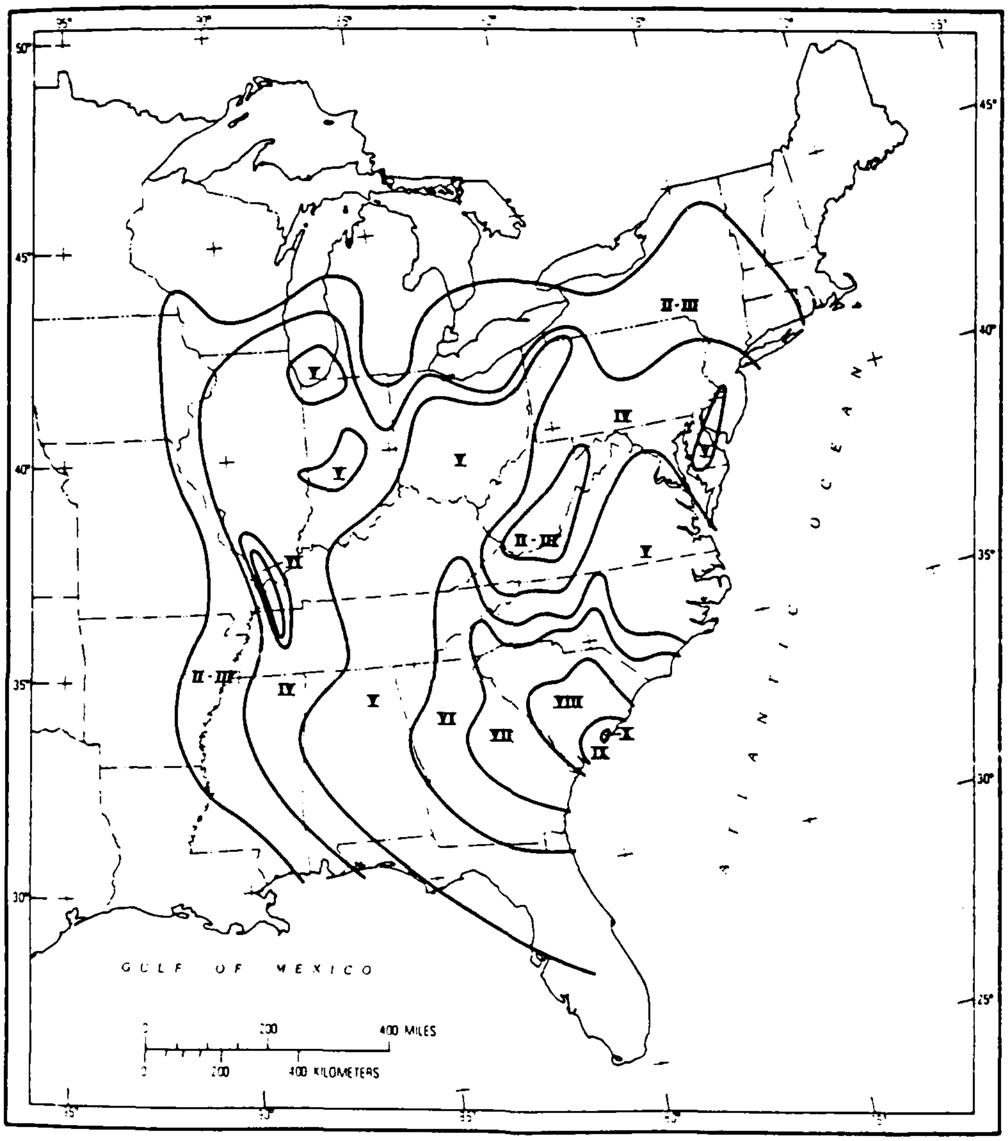


Figure 18. Isoseismal for the 1886 Charleston, South Carolinea, Earthquake (from Bollinger, 1977)

PART IV: EARTHQUAKE GROUND MOTIONS

Maximum Credible Earthquake

69. The maximum credible earthquake (MCE) is defined as the largest possible earthquake that can be reasonably expected. The largest earthquake that is interpreted for Gathright Dam is an earthquake originating from the Giles County seismic zone (see Figure 12). The maximum earthquake interpreted for Giles County is MMI IX. The MCE at Gathright Dam is the largest Giles County earthquake attenuated to the damsite.

70. The MCE at Giles County is a floating earthquake which can be moved anywhere within the source area shown in Figure 12. However, outside of this source area, the earthquake is attenuated to the site of interest according to the distance-attenuation relations shown in Figure 15. Gathright Dam is located 40 miles (65 km) from the edge of the Giles county source area. The MCE at Giles County, MMI IX, attenuated to Gathright Dam would produce an earthquake corresponding to MMI VII, a reduction of two intensity levels. An MMI VII earthquake is one intensity level higher than the seismic region hosting the damsite (see Figure 12). An MMI VII earthquake occurs at the threshold of damage for well built engineering structures (see description of MMI in Appendix C).

71. Ground motions from earthquakes originating from source areas other than Giles County (see Figure 12) would be either attenuated with distance and would therefore be less severe than the motions from a maximum Giles County earthquake, or the interpreted maximum event for these source areas is much less than the estimated maximum for Giles County. Consequently, the Central Virginia, Northern Virginia, and Southern Appalachian source areas, in addition to source areas that are more distant, are not of concern at Gathright Dam for the MCE.

Operating Basis Earthquake

72. The operating basis earthquake (OBE) is an earthquake that allows minor damage, but permits the structure to remain operational with small repairs. It is an earthquake that is expected to occur during the life of the structure. The life of the structure for purposes of this report is taken at

100 years.

73. The determination of earthquake source zones for the OBE at Gathright Dam is a difficult consideration in view of the low level of seismic activity surrounding the dam. Recurrence curves are presented in Figures 13a and 13b for the tectonic provinces and selected seismic hot spots or source zones. The recurrence curves for the tectonic provinces are considered too general for determining an operating basis earthquake at Gathright Dam. Since the dam is located midway between several seismic source zones (see Figure 12), it is more appropriate to estimate an operating basis earthquake for each source zone and attenuate this earthquake to the damsite using the attenuation and distance procedure by Chandra (1979) in Figure 15.

74. Clearly, the dominant source area within 62 miles (100 km) of Gathright Dam is Giles County (see Figure 9). Reference to Figure 13b indicates that the largest earthquake estimated to occur at Giles County during the projected 100-year operating life of Gathright Dam is approximately m_{bLg} 4.8, equivalent to MMI VIII (see Figure 14). The attenuated intensity at the damsite for the operating basis earthquake from a Giles County source is MMI VI.

75. The estimated intensity for the largest 100-year earthquake occurring in the Central Virginia seismic zone according to the curve in Figure 13b is m_{bLg} 5.0, equivalent to MMI VIII. This value is judged to be high considering that no historic earthquakes larger than MMI VII have occurred. Alternatively, an MMI VII earthquake is interpreted for this zone. The edge of the Central Virginia seismic zone is approximately 31 miles (50 km) from Gathright Dam at its closest point. As previously noted, the determination of the limits for hot spots or seismic source zones is based on the locations of historic and microearthquakes. The distance between Gathright Dam and the Central Virginia seismic zone represents a reduction of the specified MMI by a factor of one according to the attenuation-distance procedure by Chandra (1979). The attenuated intensity at the damsite for the OBE from the Central Virginia seismic zone is MMI VI.

76. The remaining seismic source area that has the potential to affect the OBE at Gathright Dam is the Southern Appalachian seismic zone (see Figure 12). The Southern Appalachian seismic zone is a broad belt of seismicity extending from Alabama to southwestern Virginia. This zone incorporates Giles County. The northeastern boundary of this zone is located approximately 37

miles (60 km) from Gathright Dam. The limits of the Southern Appalachian zone correspond approximately to the Valley and Ridge/Blue Ridge Province identified in Figure 13a by Bollinger and others (1989). The estimated 100-year earthquake for the Valley and Ridge/Blue Ridge Province is approximately m_{blg} 5.5, equivalent to MMI VIII. An MMI VIII earthquake for the Southern Appalachian zone is considered high. This estimate incorporates earthquake data from both Giles County and Eastern Tennessee, two areas of concentrated seismicity. The OBE for Giles County has been evaluated separately and should be excluded from this zone for a determination of an OBE. By excluding the Giles County zone, the major center of seismic activity becomes concentrated in Eastern Tennessee, which is well removed from the damsite. Therefore, the OBE that is interpreted for the Southern Appalachian zone is MMI VII, the historic maximum for this broad belt. The attenuated intensity at the damsite for an OBE from this zone is MMI V, a reduction of the source intensity by two intensity levels.

77. It is concluded that the maximum OBE at Gathright Dam from the various source areas identified above is MMI VI. This value is equivalent to the general maximum defined for the overall region surrounding Gathright Dam (see Figure 12).

Field Conditions

78. Ground motions from an earthquake source are characterized as being either Near Field or Far Field. Ground motions are different for each field type. Near field motions, those originating near the earthquake source, are characterized by a large range of ground motions which are caused by asperities in the fault plane, complicated reflection and refraction patterns, and focusing effects of the waves. In contrast, the wave patterns for far field motions are more orderly and they are generally muted or dampened.

79. The limits of the near field are variable, depending on the severity of the earthquake. The relationship between earthquake magnitude (M), epicentral intensity, and the limits of the near field are given in the following set of relations (from Krinitzsky and Chang, 1987).

Near Field Limits

M	MM Maximum Intensity, Io	Radius of Near Field, km
5.0	VI	5
5.5	VII	15
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45

80. Near field conditions are specified only when the site of interest is located within or near a seismic hotspot. For an MMI IX earthquake from the Giles County source, the radius of the near field is 22 miles (35 km). Gathright Dam is located further than this from the Giles County seismic source area (see Figure 12). A floating earthquake for the zone in which Gathright Dam is located in is MM VI. This zone is also far field since it is not a hotspot. Thus, far field conditions are thus recommended for the selection of ground motions at Gathright Dam.

Recommended Peak Motions

81. The parameters for earthquake motions specified in this report are horizontal peak acceleration, horizontal velocity, and duration. Duration is the amount of time in which the ground motion is equal to or above 0.05 g (gravity: 1 g = 980 cm/sec^2). Values specified are for free-field motions on rock (hard site) at the surface.

82. The ground motion parameters of interest are determined from the Krinitzsky-Chang (1987) intensity curves. The far field curves for acceleration, velocity, and duration are presented in Figures 19, 20, and 21. Values in the charts are specified for the mean, mean plus one standard deviation, and mean plus two standard deviations. The values in these charts are derived from a large world wide data base of ground motions and represent the statistical levels for the spread in motions for the different intensity levels (Krinitzsky and Chang, 1987).

Maximum Credible Earthquake

83. Motions for the MCE for Gathright Dam are as follows:

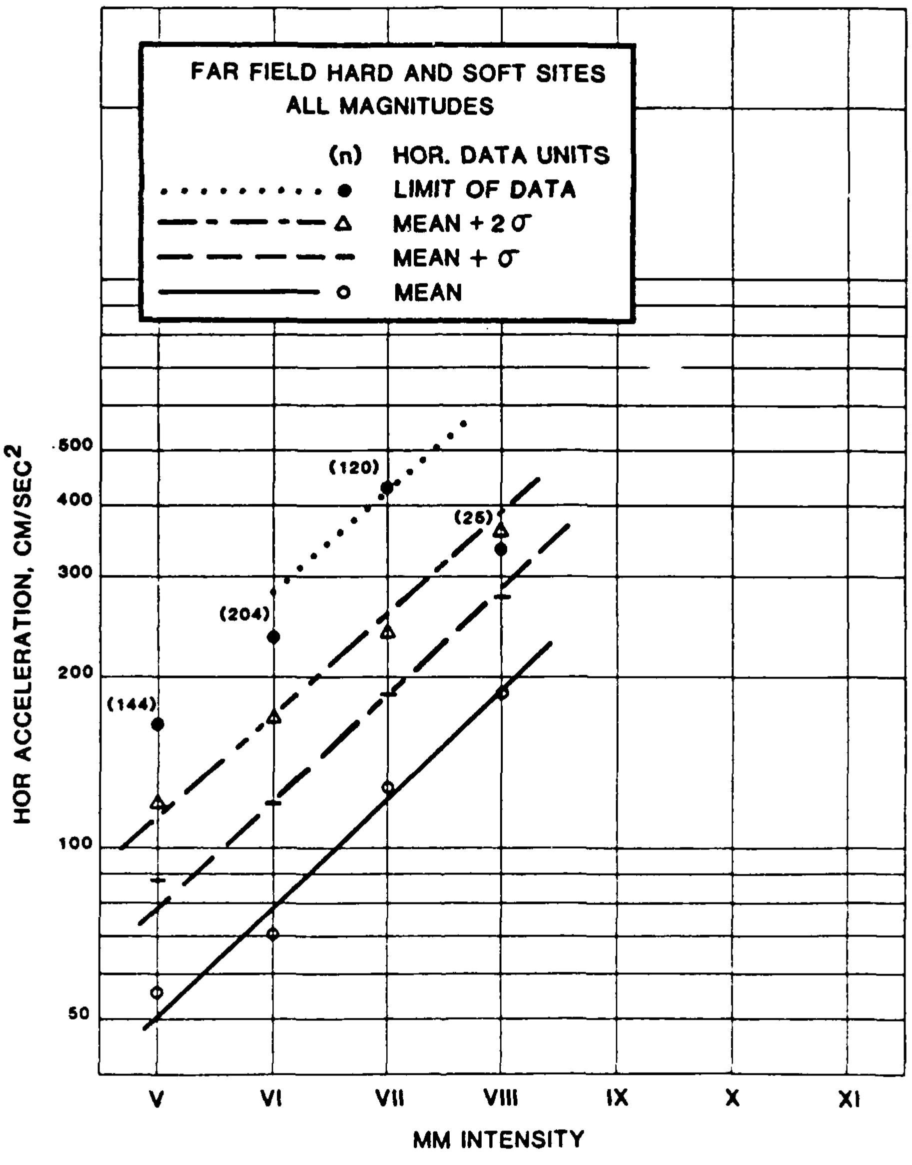


Figure 19. Chart for acceleration (from Krinitzsky and Chang, 1987)

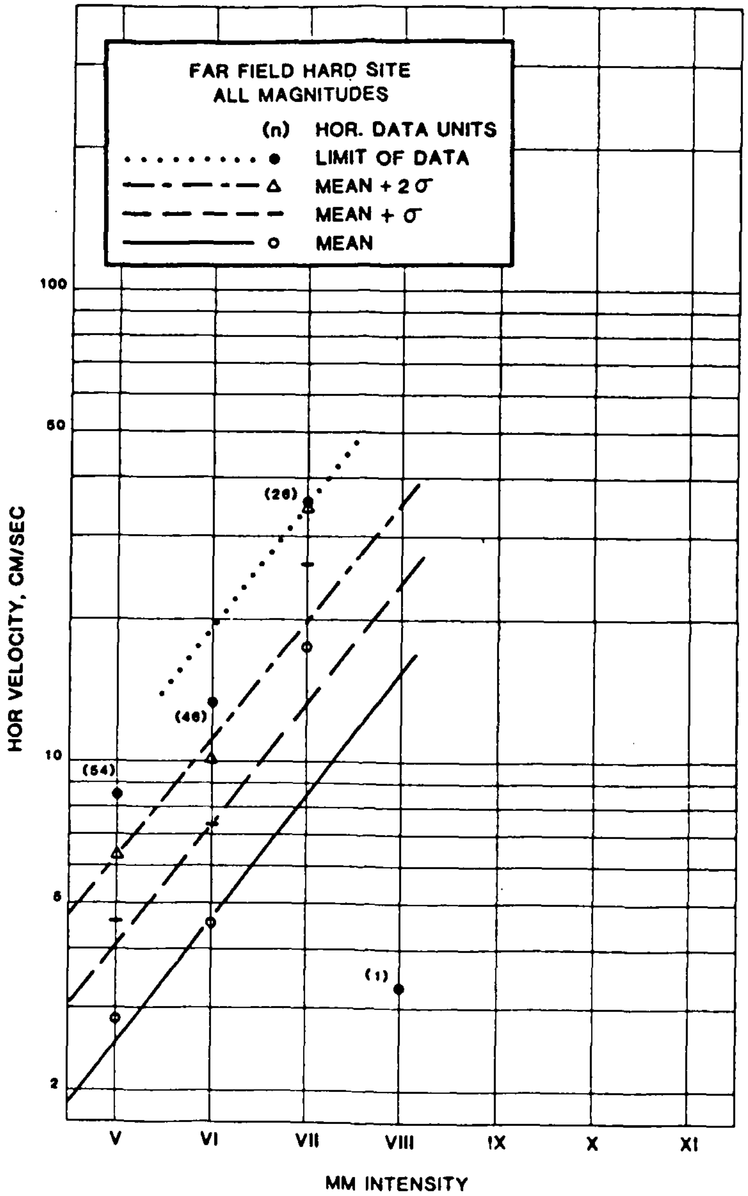


Figure 20. Chart for velocity (from Krinitzsky and Chang, 1987)

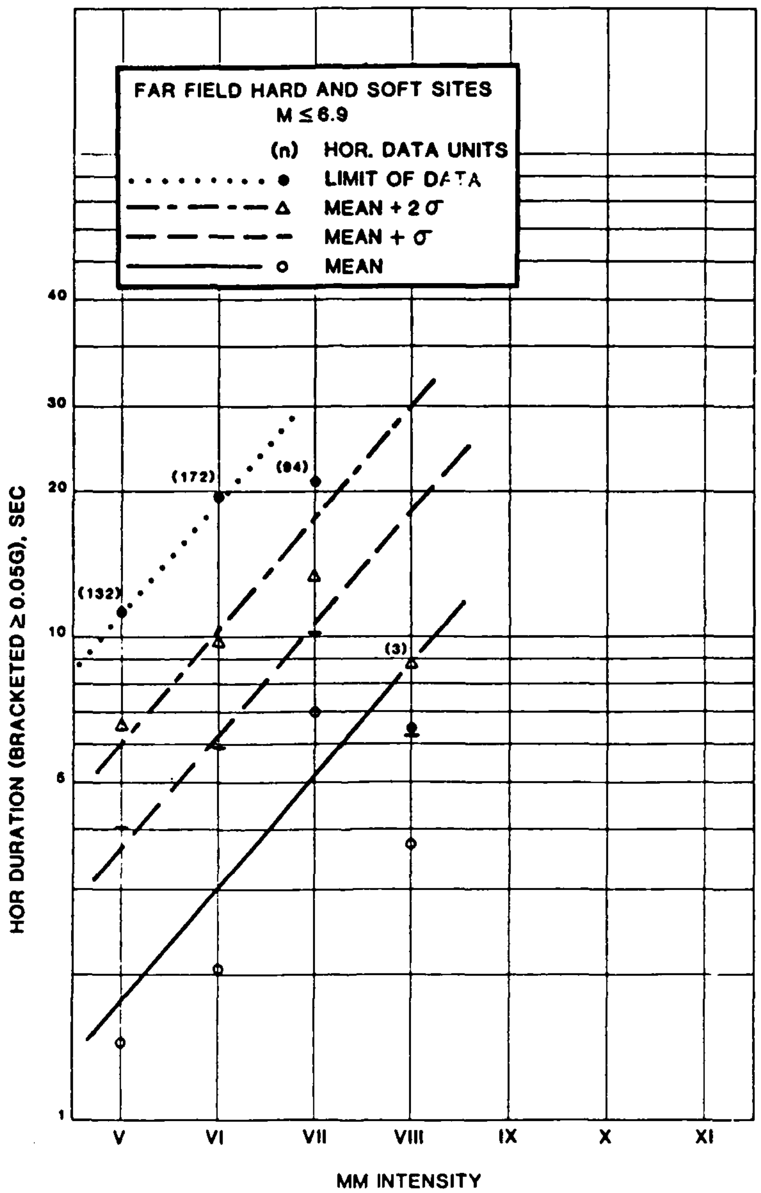


Figure 21. Chart for duration (from Krinitzsky and Chang, 1987)

Giles County Source

Hard Site, Far Field, MMIs VII, Peak Horizontal Motions

	Acceleration (cm/sec^2)	Velocity (cm/sec)	Duration Sec. $\geq$ 0.05 g
Mean	130	9	5
Mean + S. D.	190	14	11

84. Where vertical motions are desired, they may be obtained by taking 2/3 of the horizontal values.

Operating Basis Earthquake

85. Motions for an OBE at Gathright Dam are as follows:

Central Virginia - Giles County Source

Hard Site, Far Field, MMIs VI, Peak Horizontal Motions

	Acceleration (cm/sec^2)	Velocity (cm/sec)	Duration Sec. $\geq$ 0.05 g
Mean	80	5	3
Mean + S. D.	125	8	6

86. Where vertical motions are desired, they may be obtained by taking 2/3 of the horizontal values.

Recommended Accelerograms

87. Three accelerograms are recommended for use in the engineering analysis of Gathright Dam. The selected accelerograms are for motions corresponding to the mean plus one standard deviation level. Two of the recommended accelerograms are for the MCE and the other accelerogram is for the OBE. Selected accelerograms are summarized in Table 2 and are contained in Appendix F along with the associated velocity response spectra, and the quadripartite response spectra for each specified time history (from the California Institute of Technology Data Base, 1975).

88. The accelerograms are all from hard sites, a site in which the shear wave velocities are greater than 1312 ft/sec (400 meters/sec) and the underlying geologic horizon is more than 30 ft (9 meters) thick. The scaling

Table 2

Selected Earthquake Records for

Gathright Dam - Far Field

MAXIMUM CREDIBLE EARTHQUAKE

Earthquake	Record	Date	Epicentral Distance (km)	Component (Degrees)	Peak Accel (cm/sec^2)	Peak Velocity (cm/sec)	Duration* (sec)	Magnitude	Intensity	Site	Scaling
San Fernando, Los Angeles Griffith Park Observatory	0198	02/09/71	34.0	S00W	176.9	20.2	6.60	6.6	VII	Hard	1.08
San Fernando, Los Angeles CIT Seismological Laboratory	G106	02/09/71	36.1	S90W	188.6	11.6	5.88	6.6	VII	Hard	1.0

OPERATING BASIS EARTHQUAKE

Earthquake	Record	Date	Epicentral Distance (km)	Component (Degrees)	Peak Accel (cm/sec^2)	Peak Velocity (cm/sec)	Duration* (sec)	Magnitude	Intensity	Site	Scaling
San Fernando, Santa Anita Reservoir, Arcadia	P221	02/09/71	43.3	N03E	137.0	5.29	10.9	6.6	VI	Hard	0.91

* Bracketed duration: seconds greater than or equal to 0.05g

factor for the three accelerograms ranges from 0.91 to 1.08. The scaling factor is the ratio between the recommended peak acceleration and the peak acceleration occurring in the accelerogram. Records for use with the mean values may be obtained by scaling the three accelerograms accordingly. Distance from the source to the recording site for the selected records ranges from 21 to 27 miles (34 to 43 km). The peak motions and distances are considered representative of the study area.

89. The records presented in Table 2 are not the only records that may be used. Other records can be fitted to the given parameters. The accelerograms should be for analogous conditions, such as size of earthquake, focal depth (whether shallow or deep), distance from source, site condition, etc. Differences between peak values of an accelerogram and those selected parameters are accommodated by changing the scale of the accelerogram. The caution is to avoid scaling changes that are greater than two times since larger changes will affect the spectral composition.

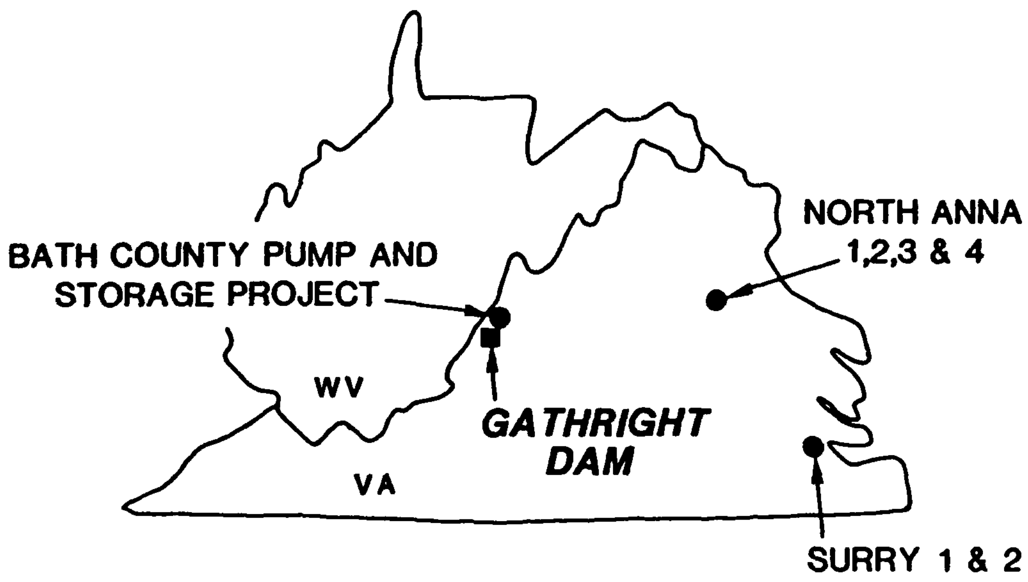
Motions for Nearby Power Plants

90. The locations of nuclear and hydroelectric power plants near Gathright Dam, the values for the safe shutdown earthquake, and the values for the operating basis earthquake are presented in Figure 22 (after Nuclear News, 1983; and Dames and Moore, 1977). Figure 22 identifies three major power plants in Virginia. There are no such facilities in West Virginia. The nearest plant to Gathright Dam is the Bath County Pump and Storage Facility.

91. The safe shutdown earthquake (SSE) is equivalent to the maximum credible earthquake. Recall that the OBE is the maximum earthquake the structure can resist and remain operational without major damage during the design life. The OBE is an engineering decision based on the cost risk considerations where there are no hazards to life.

92. Values shown for peak acceleration for the SSEs in Figure 22 need not be directly comparable to values for the maximum credible earthquake at Gathright Dam since the specification of values is dependent on the types of analyses to be performed: SSE for a pseudostatic analysis would be a mean value; for a dynamic analyses using an accelerogram, mean plus 1 S.D. would be more appropriate.

NUCLEAR & HYDROELECTRIC POWER PLANTS NEAR GATHRIGHT DAM



PLANT NAME	TYPE	ACCELERATION (g)★ SSE (MCE)	OBE	FOUNDATION
NORTH ANNA 1,2,&3	NUCLEAR	.12	.06	BEDROCK
SURRY 1&2	NUCLEAR	.15	.07	SOIL
BATH CO. PUMP & STORAGE	HYDRO	.187	.132	BEDROCK

★ SSE – SAFE SHUTDOWN EARTHQUAKE
MCE – MAXIMUM CREDIBLE EARTHQUAKE
OBE – OPERATING BASIS EARTHQUAKE

Figure 22. Locations of hydroelectric and nuclear power plants and their design earthquakes (from Nuclear News, 1983; and Dames and Moore, 1977)

Further, the seismic zone and the site condition would introduce other variations. However, the motions for Gathright Dam in Table 2 are very close to those obtained independently for the Bath County Pump and Storage Facility.

PART V: CONCLUSIONS

93. A seismic zoning was developed for the southeastern United States based on the geology and seismic history. Floating earthquakes were assigned to each seismic zone or source area for earthquakes, since no active faults have been identified for the southeastern United States.

94. The maximum earthquake interpreted for Gathright Dam is from an earthquake originating in the Giles County seismic zone. Gathright Dam is located 40 miles (65 km) from the Giles County seismic zone. This zone is the location for the second largest historic earthquake in the southeastern United States. The maximum credible earthquake at Gathright Dam, attenuated from the Giles County seismic zone, is a far field earthquake of MMI VII. Recommended peak horizontal motions for this earthquake based on the intensity curves by Krinitzsky and Chang (1987) are as follows:

Maximum Credible Earthquake

Hard Site, Far Field, MMIs VII

	Acceleration (cm/sec^2)	Velocity (cm/sec)	Duration Sec. $\geq$ 0.05 g
Mean	130	9	5
Mean + S. D.	190	14	11

95. The operating basis earthquake interpreted for Gathright Dam is a projected 100-year earthquake from either the Giles County seismic zone or the Central Virginia seismic zone. The operating basis earthquake at Gathright Dam, attenuated from these source areas, is a far field earthquake of MMI VI. Recommended peak horizontal motions for this earthquake based on the intensity curves by Krinitzsky and Chang (1987) are as follows:

Operating Basis Earthquake

Hard Site, Far Field, MMIs VI

	Acceleration (cm/sec^2)	Velocity (cm/sec)	Duration Sec. $\geq$ 0.05 g
Mean	80	[illegible]	3
Mean + S. D.	125	8	6

96. Representative accelerograms and response spectra are included (see Appendix F) that are suitable for use with the recommended ground motions identified above. Where vertical motions are considered, they may be taken at 2/3 of the horizontal.

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APPENDIX A:

GEOLOGY AT GATHRIGHT DAM

Gathright Dam

Detailed information about the general geology, foundation geology, dam design, and construction characteristics at Gathright Dam are presented in various Design Memorandum and/or Construction and Foundation Reports (U.S. Army Corps of Engineers, 1966, 1967, 1969, 1973, 1976, 1983a, 1983b, and 1983c). The information presented below and in other portions of this report is derived from these various sources.

Gathright Dam is a rolled rockfill embankment with an impervious compacted earth core (composed of silty clays and clayey silts), a double layer transition filter (sand and gravel and quarry spall material) adjacent to the core, and an outer rock shell. The axis of the dam forms an arc with radius of approximately 2,000 ft (610 meters) in length. The earthen embankment forming the dam is 1,172 ft (357 meters) long and rises 257 ft (78 meters) above the flood plain of the Jackson River. The spillway of the dam is located in a natural gap of Morris Hill on Fortney Branch Creek, approximately 2 miles (3.2 km) south of the dam. The outlet works is located in the right abutment of the dam and consists of a 261 ft (80 meter) high reinforced concrete intake tower, a 17.5 ft (5.3 meter) diameter circular diversion tunnel extending 1181 ft (360 meters) through the right abutment into a concrete stilling basin.

The foundations for the embankment and abutments are built on bedrock. The foundation geology for the dam site is shown in Figure A1 (from U.S. Army Corps of Engineers, 1983b). The rock units are composed of Devonian and Silurian age sediments. The descriptions of the individual rock units identified in Figure A1 are presented in the stratigraphic diagram in Figure A2 (from U.S. Army Corps of Engineers, 1976). The foundation is composed of limestone, sandstone, and shale. Figure A3 presents a geologic cross section along the centerline of the dam showing the distribution of the different rock units (from U.S. Army Corps of Engineers, 1983b).

Gathright Dam is located 200 to 400 ft (approximately 60 to 90 meters) downstream from the axis of the Morris Hill Anticline (see Figure A1). Consequently, the stratigraphy at the damsite dips to northwest due to folding. In general, the strike and dip of the stratigraphy in the reservoir area is very irregular because of the intense folding. Several different periods of deformation are displayed by the fold patterns.

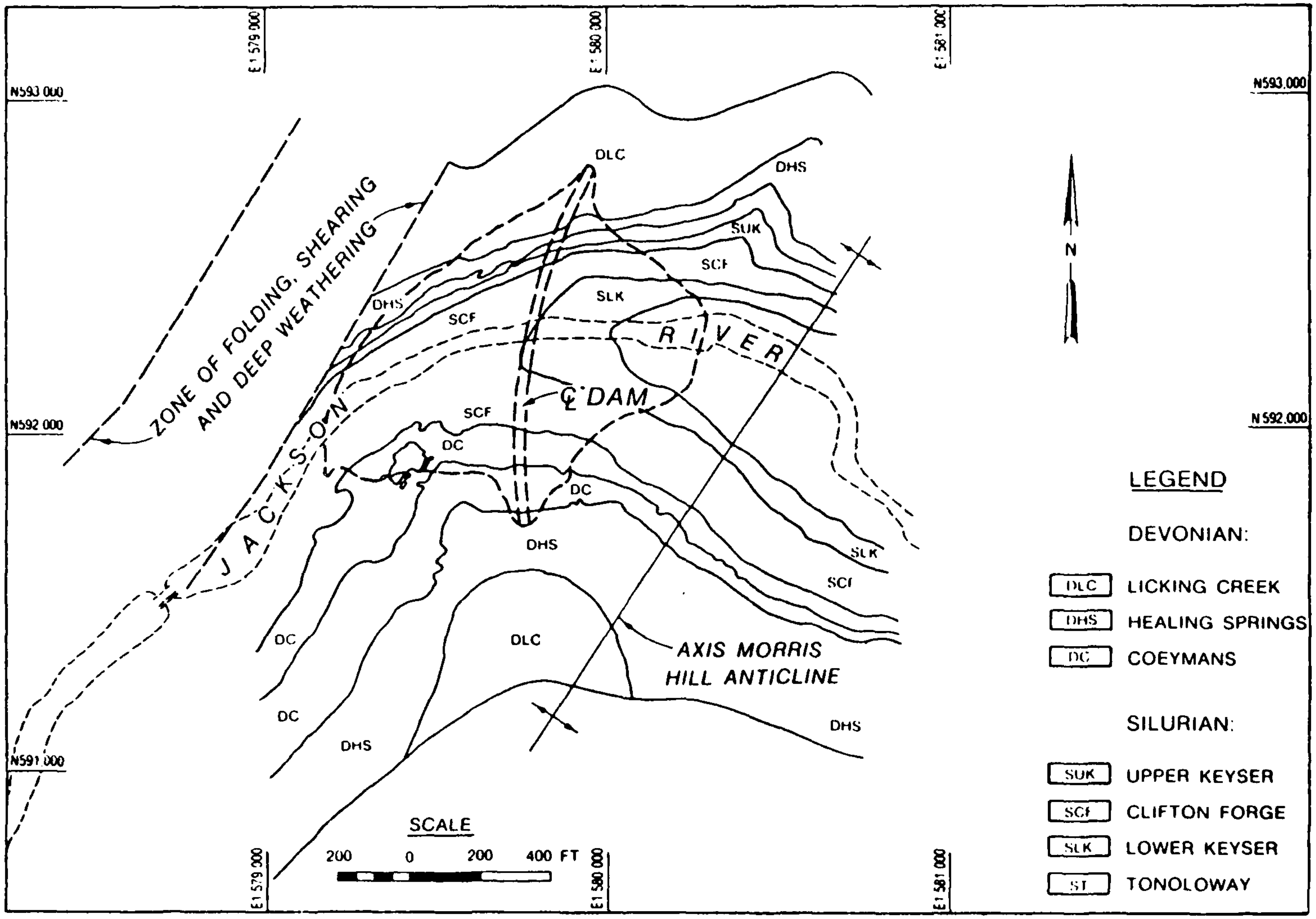

Figure A1. Foundation geology at Gathright Dam (from U.S. Army Corps of Engineers, 1983b)

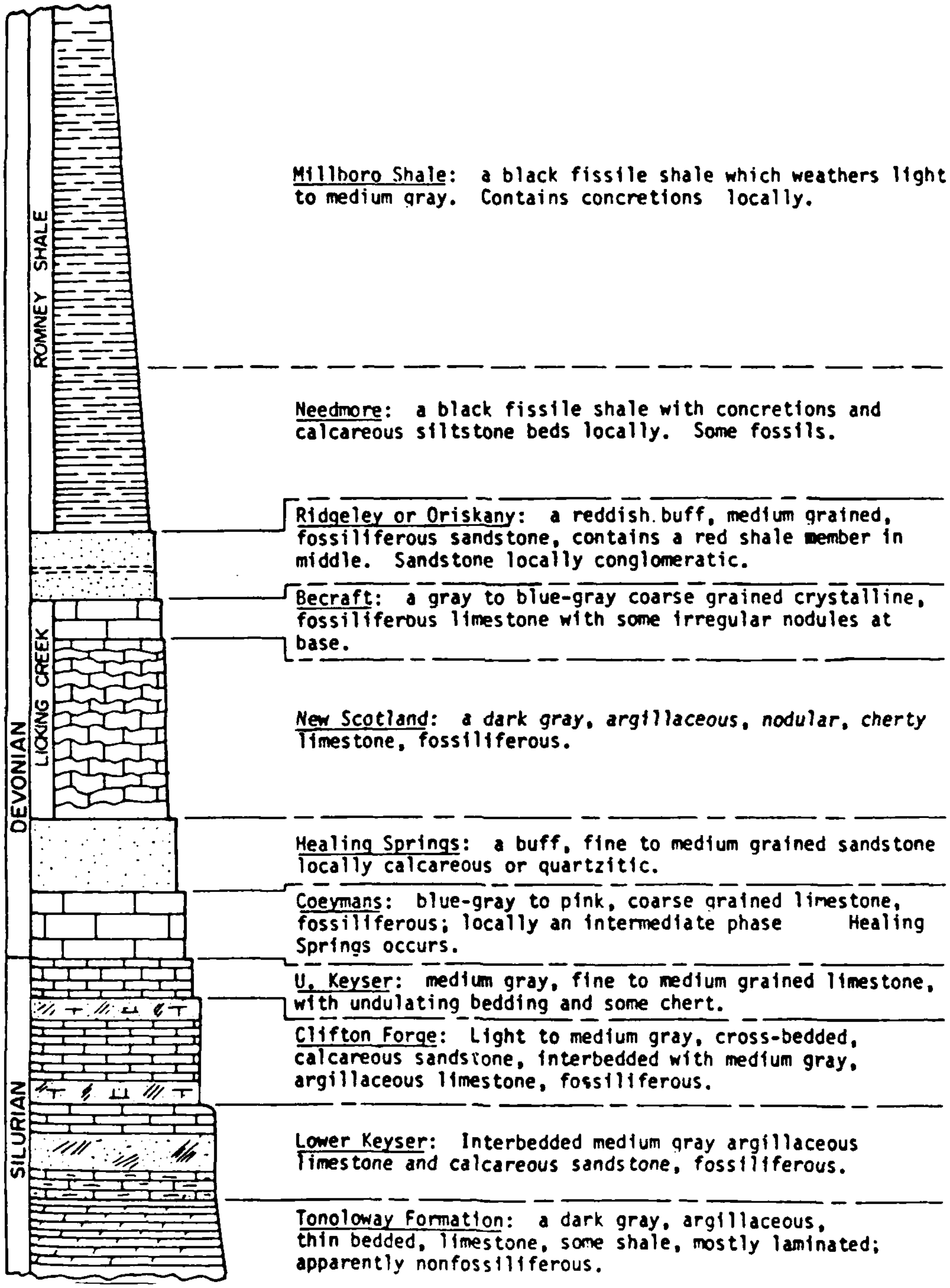

Figure A2. Stratigraphic column of rock units at Gathright Dam (from U.S. Army Corps of Engineers, 1976)

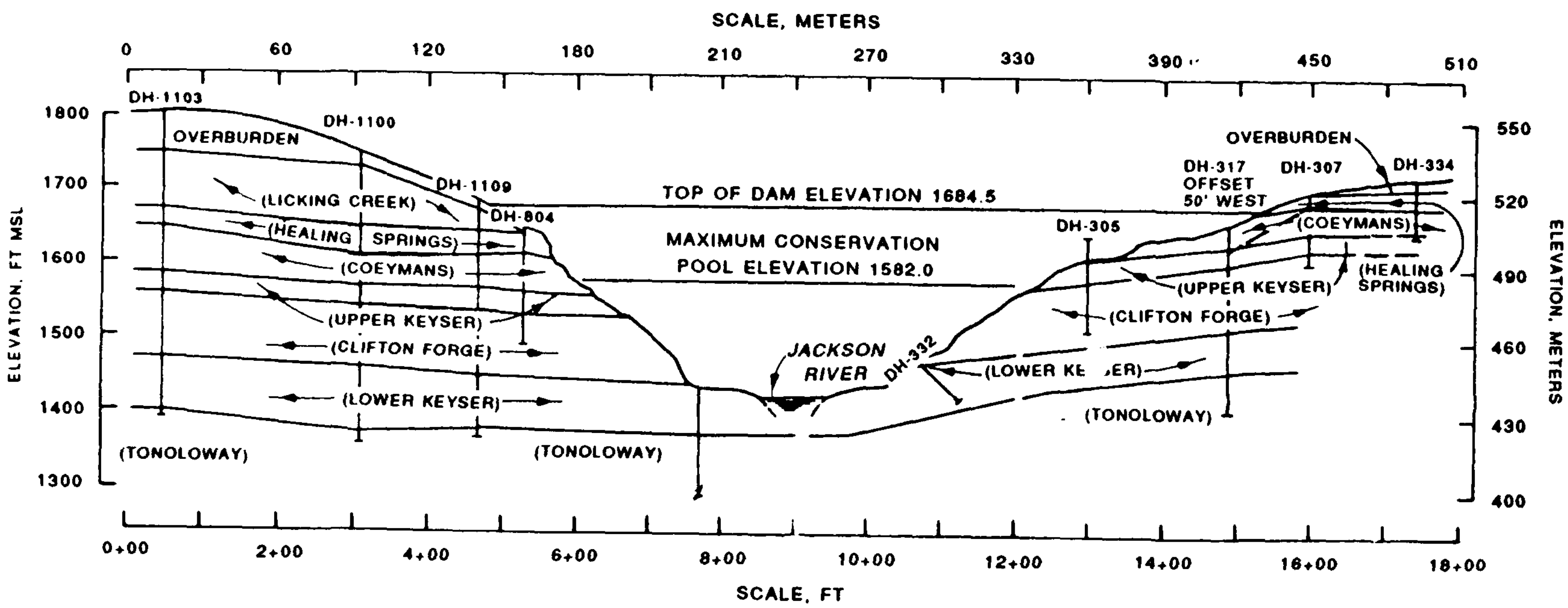

Figure A3. Geologic cross section along centerline of Gathright Dam (after U.S. Army Corps of Engineers, 1983b)

Three major fault trends were identified during the geological evaluation of the damsite and reservoir area (U.S. Army Corps of Engineers, 1976). The major trends are based on the fault orientations. The faults are parallel to the regional trend (approximately northeast-southwest), perpendicular to the regional trend (approximately east-west to northwest-southeast), and oblique to the regional trend (approximately north-south). The major faults mapped in the dam and reservoir area (see Figure 6) are generally parallel to the regional trend. The mapped faults are identified as having both strike-slip and vertical components of movement.

There were no mapped faults beneath Gathright Dam even though slick-en-slides were identified at two locations beneath the impervious core foundation (U.S. Army Corps of Engineers, 1983b; Plate II-18). At one location (south end, near the contact between the Clifton Forge Sandstone and Upper Keyser Limestone), slick-en-slides were identified as being related to bedding; while at the other location (north end, near the contact between the Clifton Forge Sandstone and the Lower Keyser Limestone), there was no reference about stratigraphy, only that slick-en-slides are present. Two northeast-southwest trending faults have been mapped a short distance upstream from the dam. The fault nearest to the dam (see Figures 6 and A1) is identified as a scissors fault, where vertical movement is analogous to a pair of scissors with displacement in opposite directions on either end of the fault. The longest fault identified is in the reservoir area, located approximately 2000 ft (610 meters) northwest from the scissors fault. In addition, faults were mapped on top of Hoover Ridge and along the spillway channel at the end of Fortney Branch.

The jointing of rocks in the dam and reservoir area has influenced drainage and cave formation in the underlying carbonate rocks. Four joint orientations are present in the vicinity of the dam. The most prominent and significant set of joints are termed oblique joints, striking between N 65° - 85° E and dipping between 60° - 85° southeast. Two sets of dip joints are present, striking N 25° - 55° W and N 65° - 85° W and dipping 60° - 90° northeast and 75° - 90° southwest, respectively. The final set of joints are identified as bedding and strike joints, striking N 20° - 50° and dipping 50° - 80° southeast and 10° - 70° northwest.

Jointing and solution cavities in the underlying foundation rocks at the dam and spillway were considered to be the major foundation problem as these features were avenues for water seepage. Detailed dental work was performed in the foundation of the dam to seal these avenues against possible leakage.

APPENDIX B:

CATALOGUE OF HISTORIC EARTHQUAKES

(North Latitude: 37.0 to 39.0, West Longitude: 79.0 to 81.0)

From Habermann, 1989

---DATE---			---TIME---			-----LOCATION-----		DEPTH	------------MAGNITUDES[1]------------				MM
YR	MO	DY	HR	MIN	SEC	LATITUDE	LONGITUDE	KM	Mb	Ms	OTHER	LOCAL	INT
1801	02	11	02			37.4 N	79.2 W						III
1801	02	11	21			37.5 N	79.1 W						II
1802	08	23	10			37.4 N	79.1 W						V
1807	05	01	09			37.4 N	79.1 W						V
1828	03	09	15			37.0 N	80.0 W						V
1828	03	10	03			37.9 N	80.0 W						V
1853	05	02	14	20		38.5 N	79.5 W						V
1856	03	21	14			37.6 N	79.0 W						III
1857	12	11	03			37.8 N	80.5 W						
1897	05	03	17	18		37.1 N	80.7 W						VII
1897	05	03	19			37.1 N	80.7 W						III
1897	05	03	21	10		37.1 N	80.7 W						III
1897	05	03	23			37.1 N	80.7 W						III
1897	05	31	18	58		37.3 N	80.7 W						VIII
1897	06	29	03			37.3 N	80.7 W						IV
1897	06	29	05			37.2 N	80.1 W						IV
1897	10	22	03	20		37.0 N	81.0 W						V
1898	02	05	20			37.0 N	80.9 W						IV
1898	02	05	20			37.0 N	80.7 W						VI
1898	02	06	02			37.0 N	81.0 W						II
1898	11	25	20			37.0 N	81.0 W						V
1899	02	13	09	30		37.0 N	81.0 W						V
1902	05	18	04			37.3 N	80.6 W						III
1905	04	29				37.3 N	79.5 W						III
1917	04	19				37.0 N	81.0 W						I
1918	04	09	18	08		38.5 N	79.0 W						II
1924	12	25				37.5 N	80.0 W						V
1924	12	26	04	30		37.3 N	79.9 W						V
1927	06	10	07	10		38.0 N	79.0 W						V
1927	06	10	07	16		38.0 N	79.0 W						V
1942	01	03	07	30		37.4 N	79.1 W						III
1942	01	03	08	30		37.4 N	79.1 W						I
1959	04	23	20	5	39.5	37.4 N	80.68 W	1				3.8 LG	VI
1959	07	07	23	17		37.3 N	80.6 W						IV
1959	08	21	17	20		37.3 N	80.6 W						IV
1963	01	17	11	40	26.8	37.3 N	80.1 W						IV
1963	01	17	14	26	50.8	37.3 N	80.1 W						IV
1968	03	08	05	38	15.1	37.0 N	80.5 W			3.9			IV
1969	11	20	01	00	09.	37.4 N	81.0 W	3	4.3				V
1974	05	30	21	28	35.3	37.46 N	80.54 W	5				3.6 LG	V
1975	03	07	12	45	13.5	37.32 N	80.48 W	5				3.0 LG	II
1975	11	11	08	10	37.6	37.22 N	80.89 W	1				3.2 LG	VI
1980	11	05	21	48	14.7	38.18 N	79.90 W	4				3.0 LG	
1981	11	23	13	14	51.	38.24 N	79.09 W	10				2.1 ML	
1981	12	04	02	35	56.4	37.0 N	80.75 W	4				2.0 LG	
1985	06	10	12	22	38.3	37.25 N	80.49 W	11				2.8 DR	IV
1986	03	26	16	36	23.9	37.25 N	80.49 W	12				2.90 MD	IV

1. Magnitude: DR = duration magnitude, CL = coda-length magnitude, LG = Lg body-wave magnitude
MD = duration or coda-length magnitude, ML = local magnitude, NU = Nuttli magnitude

APPENDIX C: GLOSSARY OF EARTHQUAKE TERMS

GLOSSARY

Accelerogram. The record from an accelerometer presenting acceleration as a function of time.

Attenuation. Characteristic decrease in amplitude of the seismic waves with distance from source. Attenuation results from geometric spreading of propagating waves, energy absorption and scattering of waves.

B-line. The slope of a straight line indicating frequency of occurrence of earthquakes versus earthquake magnitude.

Bedrock. A general term for any hard rock where it is not underlain by unconsolidated materials.

Design Spectrum. A set of curves used for design that shows acceleration velocity, or displacement (usually absolute acceleration, relative velocity, and relative displacement of the vibrating mass) as a function of period of vibration and damping.

Duration of Strong Ground Motion. The length of time during which ground motion at a site has certain characteristics. Bracketed duration is commonly the time interval between the first and last acceleration peaks that are equal to or greater than 0.05 g. Bracketing may also be done at other levels. Alternatively, duration can be a window in which cycles of shaking are summed by their individual time intervals between a specified level of acceleration that marks the beginning and end.

Earthquake. A vibration in the earth produced by rupture in the earth's crust.

1. Maximum Credible Earthquake. The largest earthquake that can be reasonably expected to occur.

2. Maximum Probable Earthquake. The worst historic earthquake. Alternatively it is (a) the 100-year earthquake or (b) the earthquake that by probabilistic determination of recurrence will occur during the life of the structure.

3. Floating Earthquake. An earthquake of a given size that can be moved anywhere within a specified area (seismotectonic zone).

4. Safe Shutdown Earthquake. That earthquake which is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to

remain functional. These structures, systems, and components are those necessary to assure: (a) the integrity of the reactor coolant pressure boundary; (b) the capability to shut down the reactor and maintain it in a safe shutdown condition; or (c) the capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the guideline exposures of this part. (Nuclear Regulatory Commission: Title 10, Chapter 1, Part 100, 30 April 1975. Same as Maximum Credible Earthquake.)

5. Operating Basis Earthquake. The earthquakes for which the structure is designed to remain operational. Its selection is an engineering decision.

Effective Peak Acceleration. A time history after the acceleration has been filtered to take out high frequency peaks that are considered unimportant for structural response.

Epicenter. The point on the earth's surface vertically above the point where the first earthquake ground motion originates.

Fault. A fracture or fracture zone in the earth along which there has been displacement of the two sides relative to one another.

1. Active Fault. A fault, which has moved during the recent geologic past (Quaternary) and, thus, may move again. It may or may not generate earthquakes. (U.S. Army Corps of Engineers 1983c.)

2. Capable Fault. An active fault that is judged capable of generating felt earthquakes.

Focal Depth. The vertical distance between the hypocenter or focus at which an earthquake is initiated and the ground surface.

Focus. The location in the earth where the slip responsible for an earthquake was initiated. Also, the hypocenter of an earthquake.

Free Field. A ground area in which earthquake motions are not influenced by topography, man-made structures or other local effects.

Ground Motion. Numerical values representing vibratory ground motion, such as particle acceleration, velocity, and displacement, frequency content, predominant period, spectral values, intensity, and duration.

Hard Site. A site in which shear wave velocities are greater than 400 m/sec and overlying soft layers are less than or equal to 15 m.

Hot Spot. A localized area where the seismicity is anomalously high compared with a surrounding region.

Intensity. A numerical index describing the effects of an earthquake on man, on structures built by him and on the earth's surface. The number is rated on the basis of an earthquake intensity scale. The scale in common use in the U.S. today is the modified Mercalli (MM) Intensity Scale of 1931 with grades indicated by Roman numerals from I to XII. An abridgement of the scale is as follows:

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeable indoors, especially on upper floors of buildings, but many people may not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration can be estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks.

XI. Few structures remain standing. Unreinforced masonry structures are nearly totally destroyed. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Liquefaction. The sudden, total loss of shear strength in a soil as the result of excess pore water pressure. The result is a temporary transformation of unconsolidated materials into a fluid.

Magnitude. A measure of the size of an earthquake related to the strain energy. It is based upon the displacement amplitude and period of the seismic waves and the distance from the earthquake epicenter.

1. Body Wave Magnitude (m_b). The m_b magnitude is measured as the common logarithm of the maximum displacement amplitude (microns) of the P-wave with period near one second. Developed to measure the magnitude of deep focus earthquakes, which do not ordinarily set up detectable surface waves with long periods. Magnitudes can be assigned from any suitable instrument whose constants are known. The body waves can be measured from either the first few cycles of the compression waves (m_b) or the 1 second period shear waves ($m_b lg$).

2. Local Magnitude (M_L). The magnitude of an earthquake measured as the common logarithm of the displacement amplitude, in microns, of a standard Wood-Anderson seismograph located on firm ground 62 miles (100 km) from the epicenter and having a magnification of 2,800, a natural period 0.8 second, and a damping coefficient of 80 percent. Empirical charts and tables are available to correct to an epicentral distance of 62 miles (100 km), for other types of seismographs and for various conditions of the ground. The correction charts are suitable up to epicentral distances of 373 miles (600 km) in southern California and the definition itself applies strictly only to earthquakes having focal depths smaller than about 19 miles (30 km). The

correction charts are suitable up to epicentral distances of about 373 miles (600 km). These correction charts are site dependent and have to be developed for each recording site.

3. <u>Surface Wave Magnitude (M_S)</u>. This magnitude is measured as the common logarithm of the resultant of the maximum mutually perpendicular horizontal displacement amplitudes, in microns, of the 20-second period surface waves. The scale was developed to measure the magnitude of shallow focus earthquakes at relatively long distances. Magnitudes can be assigned from any suitable instrument whose constants are known.

4. <u>Richter Magnitude (M)</u>. Richter magnitude is nonspecified but is usually M_L up to 6.5 and M_S for greater than 6.5.

5. <u>Seismic Movement (M_o)</u>. Seismic moment is an indirect measure of earthquake energy.

$$M_o = G\ A\ D$$

where

G = rigidity modulus

A = area of fault movement

D = average static displacement

The values are in dyne centimeters.

6. <u>Seismic Moment Scale (M_w)</u>. Expresses magnitude based on the concept of seismic moment:

$$M_w = 2/3 \log M_o - 10.7$$

7. <u>Comparison of Magnitude Scales</u>. Table 7-1 presents a comparison of values for m_b, M_L, M, log M_o, M_w and M_S.

Table 7-1. Comparison between m_b, M_L, M, log M_o, M_w and M_S scales.

m_b Body-Wave	M_L Local	M Richter	LogM_o (dyne-cm) Seismic Moment	M Moment	M_S Surface-Wave
5.0	5.4	5.4	24.2	5.4	5.0
5.5	5.9	5.9	25.0	6.0	5.8
6.0	6.4	6.7	26.1	6.7	6.7
6.5	6.9	7.5	27.3	7.5	7.5
7.0	7.5	8.3	28.6	8.4	8.3

<u>Particle Acceleration</u>. The time rate of change of particle velocity.

Particle Displacement. The difference between the initial position of a particle and any later temporary position during shaking.

Particle Velocity. The time rate of change of particle displacement.

Response Spectrum. The maximum values of acceleration, velocity, and/or displacement of an infinite series of single-degree-of-freedom systems, each characterized by its natural period, subjected to a time history of earthquake ground motion. The spectrum of maximum response values is expressed as a function of natural period for a given damping. The response spectrum acceleration, velocity, and displacement values may be calculated from each other by assuming that the motions are harmonic. When calculated in this manner these are sometimes referred to as pseudo-acceleration, pseudo-velocity, or pseudo-displacement response spectrum values.

Saturation. Where those measures of earthquake motions (acceleration, velocity, magnitude, etc.) do not increase though the earthquakes generating them may become larger.

Scaling. An adjustment to an earthquake time history or response spectrum where the amplitude of acceleration, velocity, and/or displacement is increased or decreased, usually without change to the frequency content of the ground motion.

Seismic Hazard. The physical effects of an earthquake.

Seismic Risk. The probability that an earthquake of or exceeding a given size will occur during a given time interval in a selected area.

Seismic Zone. A geographic area characterized by a combination of geology and seismic history in which a given earthquake may occur anywhere.

Soft Site. A site in which shear wave velocities are less than 400 m/sec in a surface layer 16 or more m thick.

APPENDIX D:

INSTRUMENTALLY LOCATED EARTHQUAKES IN VIRGINIA

(From Bollinger and others, 1986)

12-NOV-85 12:48:53 for the program RWVPIEQ

Input data from file ......: VPIEQ.DAT

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.	-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SGD	Error Ellipse Proj. (ERH1,AZ1;ERH2;ERZ;Q)	Magnitude Mb/Ml/I	Srce
B	-WV	1933 06 15	01:14:36.8	37-34.08	81-58.38	5.0		/				I	(23.9, -2; 6.5; 0.0;)	/ /	11
C	-WV	1958 10 23	02:29:44.3	37-12.30	81-54.30	5.0		/				I	(9.8,-83; 5.0; 0.0;)	/ /	11
D	-QC	1959 04 23	20:58:40.2	37-23.70	80-40.92	5.0		/				I	(7.0,-82; 4.2; 0.0;)	3.8/ /	11
E	-WV	1965 04 26	15:26:19.7	37-19.50	81-36.12	5.0		/				I	(4.3,-48; 2.7; 5.6;)	3.5/ /	11
F	-CV	1966 05 31	06:18:59.5	37-39.66	78- 7.74	1.6		/				I	(8.2,-44; 3.2; 8.3;)	3.6/ /	11
G	-WV	1967 12 [illegible]	12:23:33.4	37-21.60	81-32.40	2.4		/				I	(5.6,-45; 3.1; 7.6;)	/ /	11
H	-QC	1968 03 08	05:38:15.7	37-16.86	80-46.44	7.7		/				I	(3.5,-47; 3.3; 5.8;)	4.1/ /	11
JR	-QC	1969 11 20	01:00:10.6	37-23.89	80-50.02	13.2	8	7/ 5	102	10	0.4	CIB	(3.0,+56; 2.8; 3.0;B)	4.6/ /	1
K	-CV	1969 12 11	23:44:37.4	37-50.58	77-40.02	1.0		/				I	(16.0,-50; 2.9; 0.0;)	3.4/ /	11
N	-CV	1971 09 12	00:06:27.6	38- 9.00	77-35.52	4.5		/				I	(13.4,-56; 4.4; 9.1;)	3.6/ /	11
1	-CV	1974 02 28	18:38:	38-00.53	77-40.55	5.0		/			0.0	I	(, ; ; ;)	/ 1.5/	2
2R	-NV	1974 03 23	09:46:35.3	38-48.42	77-47.16	10.0	12	2/12	186	76	0.2	CID	(5.8,-30; 3.0; 7.2;C)	2.5/ /	1
R	-QC	1974 05 30	21:28:35.3	37-27.42	80-32.40	5.4		/				I	(4.6,-57; 2.8; 5.1;)	3.7/ /5	11
4	-CV	1974 06 18	15:03:	38-04.76	77-45.73	1.3		/			0.1	I	(0.5,360; 0.5; 1.6;)	/ 1.0/	2
5R	-CV	1974 08 13	13:26:30.0	37-43.15	77-47.92	13.4	7	7/ 5	343	34	0.1	CID	(4.4,-16; 2.7;11.1;D)	/ 1.5/	1
6R	-CV	1974 11 07	21:30:57.3	38-14.06	78-09.82	27.5	8	6/10	235	33	0.4	CID	(4.1,+10; 1.8; 2.9;B)	2.4/ 2.7/5	1
7	-QC	1975 03 07	12:45:13.5	37-19.20	80-28.80			/				I	(, ; ; ;)	/ 3.0/2	5
8R	-CV	1975 04 12	13:30:34.1	37-48.26	77-41.98	7.3	12	12/11	304	14	0.1	BID	(1.2,-14; 0.8; 4.1;B)	/ 1.2/	1
9R	-CV	1975 05 10	12:45:12.8	37-43.08	77-43.52	14.1	13	13/11	315	22	0.3	CID	(3.5, -1; 2.8; 6.4;C)	/ 0.8/	1
10R	-CV	1975 05 28	10:30:37.9	37-45.12	77-44.93	5.9	6	6/ 6	341	31	0.1	CID	(4.7,-17; 2.7;25.2;D)	/ 0.9/	1
11	-CV	1975 08 15	13:42:	38-02.06	77-43.73	0.5		/			0.0	I	(0.1,360; 0.1; 1.0;)	/ 1.5/	2
12	-CV	1975 09 07	19:53:	38-02.03	77-43.70	0.6		/			0.0	I	(0.1,360; 0.1; 0.9;)	/ 2.1/	2
13	-CV	1975 09 18	18:56:	38-01.97	77-43.77	0.7		/			0.1	I	(0.2,360; 0.2; 1.5;)	/ 1.7/	2
S	-QC	1975 11 11	08:10:37.6	37-13.02	80-53.52	1.0		/				I	(6.3,-35; 3.6; 0.0;)	3.2/ /4	11
15	-CV	1975 12 29	02:30:	38-28.22	77-52.24	16.1		/			0.1	I	(0.7,360; 0.7; 1.4;)	/ 1.4/	2

There have been 25 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj. (ERH1,AZ1;ERH2;ERZ;Q)	Magnitude Mb/Ml/I	Srce
17R -CV	1976 05 11	01:45:41.8	37-40.75	77-46.89	11.1	14	8/14	325	26	0.2	C|D	(2.9,-86; 2.6; 7.0;C)	/ 1.2/	1
18R -CV	1976 05 20	08:12:50.8	37-32.11	77-26.90	5.3	11	6/10	351	51	0.2	C|D	(3.8,-84; 3.3;35.8;D)	/ 1.2/	1
W -WV	1976 06 19	05:54:13.4	37-20.64	81-36.12	0.9		/				|	(6.4,-35; 3.5; 8.8;)	3.3/ /5	11
X -GC	1976 07 03	20:53:45.8	37-19.26	81- 7.62	1.0		/				|	(7.4,-39; 3.3; 0.0;)	2.1/ /	11
20 -CV	1976 07 19	13:58:	38-01.97	77-44.18	1.9		/			0.0	|	(0.1,360; 0.1; 0.6;)	/ 1.8/	2
21 -VN	1976 09 13	18:54:38.5	36-36.24	80-44.56	18.5	6	6/ 1	155	73	0.1	C|D	(5.1,-35; 2.2; 5.0;C)	3.3/ 2.9/	1
22R -CV	1976 10 30	09:32:49.8	37-38.96	77-53.62	15.0	13	9/12	336	31	0.2	C|D	(3.0,-79; 1.5; 4.4;B)	/ 1 0/	1
23R -CV	1976 10 30	10:57:19.7	37-40.44	77-55.62	15.0	14	13/14	324	30	0.2	C|D	(2.2,-72; 1.4; 1.0;A)	/ 1.3/	1
24R -CV	1976 11 03	18:04:11.1	37-21.64	77-51.02	19.7	13	13/13	341	62	0.2	C|D	(4.4, 88; 2.5;15.7;D)	/ 2.0/	1
25R -CV	1976 11 04	05:57:45.7	37-20.91	77-53.54	16.6	16	16/10	337	64	0.1	C|D	(2.6,-86; 1.7;27.6;D)	/ 2.5/	1
26 -CV	1976 12 02	18:25:	38-09.71	77-25.72	9.2		/			0.1	:	(1.8,360; 1.8; 1.5;)	/ 0.8/	2
27R -CV	1977 01 23	07:11:23.5	37-41.18	77-42.37	7.8	12	12/12	329	26	0.2	C|D	(2.2, 2; 2.2; 8.6;C)	/ 1.1/	1
28R -CV	1977 02 27	20:05:35.5	37-55.51	78-36.51	5.5	8	3/ 8	153	14	0.3	D|C	(6.8,-19; 1.8; 3.9;C)	2.5/ /4	1
29 -CV	1977 03 06	01:28:	38-00.94	77-44.79	0.4		/			0.0	|	(0.2,360; 0.2; 1.0;)	/ 0.7/	2
30 -CV	1977 04 10	03:19:	38-02.03	77-44.41	1.2		/			0.1	|	(0.1,360; 0.1; 0.7;)	/ 0.8/	2
31 -CV	1977 04 24	02:31:	38-00.42	77-45.57	0.7		/			0.1	|	(0.2,360; 0.2; 0.4;)	/ 2.0/	2
31AR-VA	1977 10 23	07:51:41.0	36-55.91	82- 8.04	10.0	7	7/ 1	191	127	0.1	C|D	(5.5,-31; 1.1; 9.0;C)	/ 2.8/	1
32 -GC	1978 01 28	23:13:23.4	37-13.68	80-44.80	4.5	3	3/ 3	243	11	0.1	D|D	(5.9, 34; 1.3; 3.0;C)	/ 1.6/	1
32A -VA	1978 03 17	18:26:34.8	36-46.77	80-44.22	15.9	9	9/ 5	154	28	0.4	C|C	(3.7,-22; 2.8; 5.8;C)	2.8/ 2.6/	1
33 -GC	1978 05 10	04:19:09.6	37-12.80	80-49.82	26.2	3	3/ 3	268	12	0.1	C|D	(4.4, 44; 1.5; 3.0;B)	/ 0.3/	1
34 -GC	1978 05 25	08:30:25.1	37- 0.01	80-47.65	12.1	5	5/ 3	269	3	0.2	C|D	(4.3, 4; 2.7; 3.8;B)	/ 1.5/	1
35 -GC	1978 06 01	01:33:01.0	37-17.99	80-41.98	17.3	3	3/ 3	170	9	0.2	C|C	(8.8, 41; 2.1; 9.1;C)	/-0.2/	1
36 -WV	1978 06 09	04:42:49.4	37-47.36	81- 9.25	14.7	4	3/ 2	340	35	0.1	D|D	(5.7,-66; 3.9;99.0;D)	/ 0.9/	1
37 -GC	1978 07 28	08:39:40.7	37-20.22	80-41.41	11.8	4	4/ 3	146	10	0.3	C|C	(4.9, 39; 2.2; 8.1;C)	/ 0.6/	1
37A -WV	1978 08 14	04:50:05.4	37-56.34	80-52.44	23.0	8	7/ 6	243	39	0.3	C|D	(3.7,-50; 1.2; 3.3;B)	/ 1.6/	1

There have been 50 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab	-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SGD	Error Ellipse Proj. (ERH1,AZ1,ERH2; ERZ;Q)	Magnitude Mb/M1/I	Srce
38	-GC	1978 08 30	02:19:38.2	37-21.71	80-40.06	8.4	4	4/ 2	158	12	0.1	C:C	(3.1, 28; 1.0; o.4;C)	/ 0.5/	1
39	-WV	1978 09 14	19:37:06.6	37-29.22	81-12.80	9.9	3	3/ 3	292	22	0.2	D:D	(6.6,-70; 3.6;17.5;D)	/-0.4/	1
41	-CV	1978 10 29	12:22:42.9	38- 1.74	78- 6.34	5.5	3	3/ 3	251	26	0.0	B:D	(1.1,-45; 0.2; 4.7;B)	/ 1.1/	1
42	-CV	1978 11 15	08:33:47.6	37-40.89	77-33.65	13.4	5	4/ 4	196	50	0.2	B:D	(1.5,-33; 1.4; 3.0;B)	3.2/ 1.8/	1
42A	-CV	1978 12 12	09:15:54.0	37-42.83	78-24.77	6.8	3	3/ 1	256	28	0.3	D:D	(9.5,-46; 4.6;29.2;D)	/ 0.0/	1
42B	-BC	1979 09 16	09:39:22.6	38- 4.78	80-14.08	11.3	7	7/ 6	199	28	0.2	C:D	(4.0,-27; 1.4; 4.7;B)	/ 1.6/	1
42C	-BC	1979 09 19	00:45:57.3	38- 5.65	80-13.93	16.5	10	10/10	187	28	0.2	C:D	(1.9,-34; 0.6; 5.2;C)	/ 1.8/	1
42D	-GC	1979 10 31	08:32:47.8	37-36.23	81-10.68	7.2	4	3/ 2	265	30	0.0	D:D	(6.7,-80, 2.9; 8.9,C)	/ 0.7/	1
43	-CV	1979 11 06	03:04:51.3	37-25.68	78-13.15	6.8	10	9/ 7	103	28	0.2	B:C	(1.0,-82, 0.6; 1.8,A)	1.3/ 1.4/	1
44	-CV	1979 11 12	07:21:53.8	37-43.33	77-28.76	5.0	5	5/ 5	173	54	0.2	C:D	(0.9,-81; 0.7;21.4;D)	1.2/ 1.1/	1
45	-VA	1980 01 06	13:50:55.7	36-37.89	81-34.03	3.6	10	10/ 8	323	80	0.4	D:D	(6.6,-47; 4.1; 3.2;C)	1.0/ 1.6/	1
46	-GC	1980 02 18	03:58:55.3	37-25.78	80-35.54	13.0	9	5/ 9	199	22	0.3	B:D	(1.7, 49; 1.2; 3.6;B)	/ 1.1/	1
47	-WV	1980 04 10	22:33:15.7	37-29.21	81- 5.16	5.0	3	3/ 2	253	17	0.2	D:D	(14.8,-52; 2.1;13.9;D)	/ 0.7/	1
48	-NC	1980 04 22	03:14:04.6	36-23.88	80-36.50	0.5	10	10/ 6	128	92	0.3	C:D	(2.9,-77; 1.7; 6.4,C)	2.8/ 2.2/1	1
49	-CV	1980 04 26	03:59:54.8	37-46.35	77-34.92	0.7	7	7/ 7	206	35	0.2	B:D	(1.5,-55; 0.8, 2.2;A)	3.0/ 1.4/	1
50	-CV	1980 05 18	03:31:19.9	37-34.85	77-56.27	28.5	4	3/ 4	215	28	0.3	C:D	(4.4,-77; 2.5;12.2;D)	/ 0.9/	1
51	-CV	1980 05 18	22:33:55.4	37-58.20	78- 4.08	5.6	4	4/ 1	146	17	0.1	C:D	(4.7,-34; 2.1;18.3;D)	/ 0.0/	1
53	-NA	1980 08 04	10:13:32.7	38- 3.97	77-45.86	4.9	8	8/ 7	111	7	0.1	A:B	(0.7,-41; 0.5; 1.6;A)	/ 0.7/	1
55A	-BC	1980 09 21	10:02:46.3	38-10.49	80- 4.20	3.1	8	6/ 5	193	14	0.3	C:D	(3.1,-24; 1.7; 3.3;B)	/ 1.4/	1
57	-NA	1980 09 26	01:31:57.8	38- 4.16	77-46.11	0.4	7	7/ 5	116	7	0.2	C:B	(1.3,-32; 0.9;52.3;D)	3.5/ 2.0/	1
57A	-NA	1980 09 26	05:04:15.7	38- 4.67	77-43.00	4.5	3	3/ 3	222	6	0.2	D:D	(7.5, 88, 2.7; 9.4;C)	/ 0.1/	1
58	-GC	1980 10 09	01:47:01.1	37-13.01	80-49.32	23.5	3	2/ 3	345	11	0.3	D:D	(7.2, 40; 2.3; 4.9,C)	/-0.2/	1
59	-NA	1980 10 11	22:40:28.5	38- 7.20	77-48.67	2.4	4	3/ 3	168	6	0.1	C:C	(5.5,-49, 0.8; 6.8;C)	/ 0.7/	1
60	-GC	1980 10 14	01:20:04.6	37- 4.69	80-13.82	11.0	14	11/13	171	22	0.4	C:C	(2.0, 13; 1.1; 3.1;B)	/ 1.7/	1
61	-BC	1980 10 16	03:48:07.6	38- 3.98	80-12.88	10.0	7	6/ 7	180	27	0.2	B:D	(2.9,-34; 0.9; 3.9;B)	/ 1.1/	1

There have been 75 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj. (ERH1,AZ1;ERH2;ERZ;Q)	Magnitude Mb/Ml/I	Srce
61A -BC	1980 11 05	21:48:14.7	38-10.70	79-54.11	3.8	21	19/10	77	5	0.2	B:A	(0.7,-25; 0.4; 1.0;A)	/ 3.0/1	1
62 -BC	1980 11 25	07:44:04.0	38- 5.70	80- 7.35	15.3	4	4/ 4	324	18	0.1	C:D	(2.9,-42; 2.8; 3.4;B)	/ 0.6/	1
63 -GC	1980 12 02	07:47:38.2	37-25.08	80-32.25	12.2	6	5/ 5	113	25	0.3	C:C	(3.2, 51; 2.0; 7.4;C)	/ 0.4/	1
63A -CV	1981 01 19	21:54:19.3	37-43.94	78-26.18	2.9	7	5/ 7	182	28	0.2	C:D	(1.2,-76; 0.8;18.2;D)	/ 0.6/	1
63B -CV	1981 01 21	16:29:58.1	37-46.08	78-24.98	5.8	7	6/ 3	175	24	0.1	C:C	(1.0, 54; 0.6; 5.1;C)	0.3/	1
64A -CV	1981 02 11	13:44:16.4	37-43.22	78-26.40	5.7	14	14/ 9	79	29	0.2	B:C	(0.7, 68; 0.6; 2.2;A)	3.4/ 2.6/4	1
64B -CV	1981 02 11	13:50:31.4	37-44.87	78-24.69	10.1	12	12/ 7	114	26	0.2	B:C	(1.0, 36; 0.7; 1.6;A)	3.2/ /4	1
64C -CV	1981 02 11	13:51:38.6	37-43.26	78-27.02	7.3	9	8/ 6	128	29	0.2	B:C	(1.1, 60; 0.8; 4.1;B)	2.9/ 2.2/3	1
64D -CV	1981 02 12	10:41:59.0	37-44.03	78-25.17	12.5	3	2/ 3	276	28	0.2	C:D	(2.6, 61; 1.8;14.9;D)	/-0.6/	1
65 -CV	1981 03 20	04:02:03.0	37-31.18	77-40.75	6.9	5	2/ 5	291	49	0.1	C:D	(1.9, 85; 1.0;27.2;D)	/ 0.6/	1
66 -CV	1981 04 09	07:12:54.4	37-28.87	77-49.26	0.8	11	8/10	129	43	0.3	B:C	(1.2, 89; 0.8; 2.1;A)	/ 2.1/	1
67 -CV	1981 04 09	07:34:36.0	37-27.95	77-51.96	1.1	4	2/ 4	267	42	0.3	C:D	(4.4, 68; 2.3;99.0;D)	/ 0.4/	1
68 -BC	1981 04 11	15:29:25.7	38-13.56	79-50.21	10.2	3	3/ 3	254	6	0.1	D:D	(6.6, 55; 1.1; 3.8;C)	/-0.6/	1
69 -CV	1981 04 16	13:49:20.5	37-36.52	78-12.89	15.5	3	3/ 3	189	23	0.1	D:D	(10.7,-65; 0.6; 4.7;D)	/ 0.1/	1
70 -BC	1981 06 06	08:05:58.7	38-12.45	79-30.87	14.3	6	5/ 6	159	13	0.5	D:C	(2[illegible].5, 45; 4.7;25.0;D)	/ 0.7/	1
71 -CV	1981 07 30	11:59:48.5	38-11.66	78- 5.26	6.0	10	8/10	180	30	0.3	C:C	(2.7,-22; 1.2; 6.7;C)	3.1/ 1.4/3	1
72 -GC	1981 08 24	11:50:11.2	36-56.71	80-44.76	16.8	7	6/ 7	183	11	0.2	B:D	(1.6,-43; 1.1; 2.8;B)	/ 1.0/	1
73 -GC	1981 11 12	06:24:14.0	37-14.10	80-44.99	9.2	5	2/ 4	223	10	0.2	C:D	(3.9,-67; 1.8;10.7;D)	/ 0.7/	1
74 -CV	1981 11 23	13:14:51.0	38-14.48	79- 5.58	9.8	16	12/11	175	50	0.3	B:C	(1.6, 2; 0.6; 1.4;A)	2.1/ 2.1/3	1
75 -GC	1981 12 04	02:35:56.4	36-59.99	80-44.77	3.5	16	14/ 7	157	7	0.4	C:C	(1.9,-20; 1.2; 2.4;A)	/ 2.0/	1
77 -CV	1982 01 13	13:16:25.0	37-44.95	78- 4.20	9.4	10	6/ 9	170	6	0.2	A:C	(0.8,-67; 0.6; 0.8;A)	/ 1.5/	1
78 -CV	1982 01 18	06:11:41.2	37-54.31	77-50.35	7.4	6	6/ 5	171	9	0.1	B:C	(1.1,-36; 0.6; 2.2;A)	/ 0.3/	1
79 -CV	1982 02 20	04:34:25.8	37-29.1[illegible]	7[illegible]2.40	0.8	9	8/ 7	145	49	0.1	C:C	(0.8,-88; 0.4;79.8;D)	/ 1.5/1	1
80 -CV	1982 04 11	20:01:14.6	37-43.78	78-25.12	1.3	4	4/ 4	277	28	0.1	C:D	([illegible].9, 24; 0.8;28.1;D)	/ 0.9/	1
81A -CV	1982 05 04	14:54:02.2	37-33.84	78-27.76	5.2	6	5/ 6	139	40	0.3	C:C	(2.8,-80; 1.1; 8.3;C)	/ 1.4/	1

There have been 100 earthquakes listed so far

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.	-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj. (ERH1,AZ1;ERH2;ERZ;Q)	Magnitude Mb/M1/I	Srce
81B	-CV	1982 05 04	14:57:31.2	37-33.13	78-25.51	0.7	4	2/ 4	238	39	0.1	C:D	(1.3,-81; 0.5;82.4;D)	/ 0.7/	1
82	-CV	1982 05 06	07:18:10.9	37-51.24	77-34.71	9.7	10	10/ 8	153	17	0.2	B:C	(1.0,-82; 0.7; 2.3;A)	/ 2.0/1	1
83	-GC	1982 05 18	03:16:33.9	37- 7.72	80-29.97	10.5	12	11/ 7	148	9	0.2	B:C	(1.3, 2, 0.8; 1.4;A)	/ 1.6/	1
84	-CV	1982 06 16	18:40:58.6	38- 7.63	78-50.44	10.9	6	6/ 5	125	37	0.1	A:C	(0.7, 9, 0.6; 1.7;A)	/ 2.1/1	1
85	-WV	1982 06 23	16:17:34.1	37-52.21	80-57.42	11.1	17	16/ 9	113	33	0.2	B:C	(1.3,-63; 0.9; 2.0;A)	/ 2.5/	1
86	-CV	1982 06 25	23:03:47.0	37-49.86	77-30.12	13.5	9	9/ 9	166	23	0.1	A:C	(0.9, -6; 0.8; 1.5;A)	/ 1.8/	1
87	-CV	1982 09 20	12:15:32.0	37-49.30	77-29.76	10.6	10	10/10	168	24	0.2	B:C	(0.9,-88; 0.6; 1.5;A)	/ 1.5/	1
88	-GC	1983 01 08	15:53:55.8	37-19.65	80-36.93	4.1	5	4/ 4	139	16	0.2	B:C	(1.9,-13; 1.2; 4.2;B)	/ 1.2/	1
89	-BC	1983 01 21	05:33:20.4	38- 4.03	80- 8.64	17.8	4	4/ 4	327	21	0.1	C:D	(3.3,-44; 2.7; 4.2;B)	/ 0.4/	1
90	-GC	1983 01 25	20:38:58.3	37-23.15	80-30.32	16.7	19	19/17	81	13	0.3	B:A	(0.9,-48; 0.6; 1.2;A)	/ 1.8/	1
91	-VA	1983 02 10	06:18:59.5	36-55.70	82-58.26	1.3	8	8/ 7	189	72	0.3	C:D	(4.0,-29; 0.8; 5.9;C)	/ 2.2/	1
92	-GC	1983 04 20	18:09:56.6	37-20.93	80-49.99	10.4	7	7/ 6	129	5	0.2	B:B	(1.8, 25; 0.9; 2.1;A)	/ 1.2/	1
93A	-GC	1983 05 12	00:23:07.0	37-11.49	80-43.88	14.3	5	3/ 5	202	15	0.2	B:D	(2.1,-27; 1.3; 4.0;B)	/-0.5/	1
93B	-GC	1983 05 17	02:02:47.7	37-15.27	80-44.09	6.9	7	5/ 7	132	9	0.3	C:B	(2.0,-16; 1.4; 5.2;C)	/-0.1/	1
94	-GC	1983 05 26	01:04:44.8	37-30.35	80-18.95	9.0	19	18/14	109	8	0.2	B:B	(0.9,-37; 0.8; 1.8;A)	2.6/ 2.2/	1
95A	-WV	1983 06 10	00:18:40.5	37-56.88	80-09.78	23.6	12	10/12	156	30	0.2	B:C	(2.2,-51; 0.7; 3.8;B)	/ 1.2/	1
95B	-WV	1983 06 10	00:24:57.0	37-57.04	80-11.31	18.4	13	13/13	160	31	0.2	B:C	(1.4,-49; 0.4; 3.6;B)	/ 1.2/	1
95C	-WV	1983 06 10	00:31:08.3	37-56.30	80-10.08	13.0	12	10/11	156	31	0.3	B:C	(2.7,-56; 0.9; 3.3;B)	/ 0.4/	1
96	-CV	1983 07 03	16:29:24.9	37-38.43	78-22.40	3.5	13	8/13	170	29	0.3	C:C	(1.5,-75; 0.9; 4.2;B)	/ 1.2/	1
97	-GC	1983 07 10	14:05:39.4	37-16.22	80-45.22	7.6	7	7/ 7	89	6	0.3	B:A	(1.2,-18; 1.2; 2.9;B)	/ 1.0/	1
98	-WV	1983 07 20	04:41:40.9	37-53.07	80-41.47	11.0	11	10/11	208	35	0.3	B:D	(2.6,-53; 0.8; 2.7;B)	/ 1.6/	1
98A	-WV	1983 07 25	03:27:00.2	37-29.75	81-21.11	29.0	4	3/ 4	299	32	0.1	C:D	(4.9,-81; 2.6; 6.5;C)	/ 0.6/	1
99	-VA	1983 07 30	06:31:52.8	36-41.54	81-38.28	3.0	8	5/ 8	187	43	0.3	C:D	(2.4,-45; 1.2; 6.1;C)	1.5/	1
100	-CV	1983 08 10	12:29:34.1	37-46.35	78-25.46	11.2	8	8/ 6	118	23	0.3	C:C	(3.4,+28, 1.3, 4.9;B)	/ 1.8/	1
101	-GC	1983 08 25	05:04:34.8	37-19.47	80-43.68	14.7	4	3/ 4	279	6	0.2	C:D	(3.0,+29; 1.8, 3.8;B)	/ 0.0/	1

There have been 125 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab -Reg	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj. (ERH1,AZ1;ERH2;ERZ;Q)	Magnitude Mb/Ml/I	Srce
102A-OC	1983 11 13	16:51:06.7	37-33.36	80-45.29	10.0	4	3/ 4	171	9	0.1	B:C	(1.0,-26; 0.5; 2.2;A)	/ 0.4/	1
102B-OC	1983 11 13	17:06:14.1	37-33.53	80-45.23	9.1	4	2/ 4	253	9	0.1	B:D	(1.5,-16; 0.8; 3.7;B)	/-0.8/	1
102C-OC	1983 11 13	17:50:50.1	37-33.55	80-45.17	11.0	5	3/ 5	174	9	0.1	B:C	(1.5,-22; 0.9; 3.5;B)	/ 0.7/	1
103A-OC	1983 11 25	16:22:05.0	37-33.57	80-45.54	8.9	3	1/ 3	360	8	0.0	D:D	(5.5,+63; 3.9;10.4;D)	/-1.2/	1
103B-OC	1983 11 25	16:27:47.8	37-34.10	80-44.71	11.9	5	5/ 5	184	9	0.1	A:D	(0.8,-09; 0.6; 1.7;A)	/ 0.7/	1
103C-OC	1983 11 25	16:50:00.8	37-34.09	80-45.03	11.5	4	2/ 4	260	8	0.1	C:D	(2.7,-13; 1.4; 5.6;C)	/-0.8/	1
104 -OC	1983 12 09	00:11:57.9	37-12.05	80-47.15	12.4	17	17/10	98	13	0.2	B:B	(0.7,-52; 0.6; 1.2;A)	/ 1.3/	1
105 -WV	1983 12 23	10:51:21.9	37-45.94	80-50.21	13.7	6	5/ 6	289	20	0.2	C:D	(2.3,-39; 1.5; 2.3;A)	1.6/ 0.3/	1
106 -CV	1984 02 06	12:27:03.4	37-34.38	78-08.95	0.4	4	4/ 5	174	25	0.1	C:C	(0.5,-83; 0.3;50.5;D)	/ 1.1/	1
107 -OC	1984 03 11	04:01:37.8	37-29.01	80-53.56	14.3	9	3/ 9	161	13	0.2	B:C	(2.1,-62; 1.2; 2.8;B)	/ 1.0/	1
108 -CV	1984 04 12	23:46:30.6	37-56.56	78-01.47	06.1	8	4/ 4	227	14	0.1	C:D	(3.9,-38; 0.6; 4.5;B)	/-0.8/	1
109 -CV	1984 05 29	11:29:35.0	38-06.42	78-47.58	07.4	5	5/ 5	329	33	0.1	C:D	(2.2,-10; 1.4; 7.2;C)	/ 1.3/	1
110 -OC	1984 07 02	19:51:38.7	37-17.07	80-43.24	11.2	9	7/ 9	89	7	0.2	B:A	(1.1,+02; 0.9; 2.3;A)	/ 1.4/	1
111 -CV	1984 08 17	18:05:46.9	37-52.05	78-19.42	08.2	13	13/ 3	104	18	0.2	B:C	(0.9,+18, 0.6, 1.7;B)	4.2/ 4.0/5	1
112 -WV	1984 10 09	05:33:31.5	37-42.77	80-53.44	13.4	9	9/ 9	222	14	0.2	B:D	(0.8,-50; 0.5; 0.6;A)	/ 2.1/	1
113 -CV	1984 10 17	08:57:40.7	37-56.05	77-30.41	14.7	9	8/ 9	202	17	0.2	B:D	(0.9,-27; 0.5; 0.9;A)	/ 1.1/	1
114 -OC	1984 11 17	03:17:28.3	37-15.94	80-43.61	10.3	6	4/ 6	118	8	0.1	A:D	(0.4,+68; 0.3; 1.0;A)	/ 0.0/	1
115 -CV	1984 12 02	12:29:34.1	37-26.52	77-55.57	4.5	6	3/ 6	258	42	0.2	C:D	(0.9,+90; 0.6; 4.2;C)	/ 1.1/	1
116 -BC	1984 12 21	13:12:21.9	38-11.85	80-12.49	5.8	12	10/12	223	26	0.4	C:D	(2.0,-28; 0.5; 2.0;B)	/ 1.6/	1
117 -CV	1985 04 22	18:21:16.0	37-36.15	78-35.91	4.5	8	7/ 8	111	43	0.8	C:C	(1.1,-90; 0.5; 4.1;C)	/ 2.0/	1
118 -OC	1985 06 10	12:22:38.3	37-14.89	80-29.12	11.1	9	9/ 5	99	6	0.3	B:B	(0.9,-17; 0.9; 2.0;B)	3.2/ 2.8/4	1
119 -WV	1985 06 14	07:57:10.2	37-32.05	81-01.19	2.4	5	4/ 3	242	17	0.3	D:D	(3.6,-52; 1.1; 4.4;C)	/ 0.8/	1
120 -VA	1985 06 19	22:28:08.9	37-13.30	82-02.30	0.5	13	13/ 7	183	89	0.4	C:D	(1.6,-27; 1.0; 3.8;C)	/ 3.6/	1
121 -OC	1985 07 02	05:38:24.9	37-14.71	80-34.03	7.7	3	3/ 3	185	14	0.1	B:D	(0.8,+02; 0.4; 2.2;B)	/-0.6/	1

There are 149 earthquakes in this list

Abbreviations For Regions:

- BC: Bath County, Virginia, area,
- CV: Central Virginia Seismic Zone,
- GC: Giles County, Virginia, Seismic Zone,
- NA: North Anna, Virginia, area,
- KY: Kentucky area,
- NV: Northern Virginia area,
- SC: South Carolinia area,
- TN: Tennessee area,
- VN: Virginia / North Carolina area,
- VW: Virginia / West Virginia area,
- WV: West Virginia,

R Events that have been relocated for special studies. *Calculated using either, a new technique* (JHD, JED, HYPOELLIPSE, etc.) or a different velocity model.

Sources and/or References

1: VTSO records, NRC reports, SEUSSN Bulletins, or G. A. Bollinger personal files.
2: Dames and Moore, 1977. 'A Seismic Monitoring Program At The North Anna Site In Central Virginia', - January 24, 1974 Through August 1, 1977. Submitted to VEPCO, 1977.
5: Coffman, Jerry L., and C. W. Stover, 19XX. U. S. Earthquakes, 19XX; annual publication by NOAA and the USGS.
7: USGS Preliminary determination of epcenters, 19XX, monthly listings.
11: Dewey and Gordon, 1987. Relocation of major eastern North American earthquakes using JED/JHD

APPENDIX E:

ESTIMATION OF THE MAXIMUM MAGNITUDE EARTHQUAKE FOR THE GILES COUNTY, VIRGINIA, SEISMIC ZONE

by

G. A. Bollinger

Estimation of the Maximum Magnitude Earthquake

for the

Giles County, Virginia, Seismic Zone

Prepared for

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Vicksburg, Mississippi 39181

by

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Blacksburg, Virginia 24060

February, 1989

EXECUTIVE SUMMARY

The maximum magnitude earthquake expected from the Giles county, Virginia seismic zone is estimated. Of the various techniques employed to obtain estimates for such maximum seismic events, three are applicable to the data bases available for eastern United States seismicity : (1) Adding an increment to the maximum historical earthquake in the zone, (2) Extrapolation of the magnitude recurrence curve for the zone, and, (3) Magnitudes based on estimates of the fault area of the zone. Each of these techniques has associated uncertainties both in their applicability to the zone under consideration as well as in the determination of the key parameters involved. The process of maximum magnitude estimation is intrinsically subjective and depends directly on the experience and judgment of the analyst.

Application of the above three techniques to the Giles county, Virginia, seismic zone leads to the following results :

Ms = 6.9 from adding a 1.0 increment to the maximum historical earthquake known to have occurred in the zone (May 31, 1897 ; MMI = VIII ; mb = 5.8, Ms = 5.9),

Ms = 6.95 from extension of the magnitude-recurrence curve, and

Ms = 6.57 from the average of six estimates for the fault zone area ranging from 112 sq km (Ms = 6.34) to 300 sq km (Ms = 6.76).

For a single estimate of maximum magnitude the average of the above three values, rounded to the nearest one-tenth, should be used. That value is :

Ms = 6.8 or equivalently, **mb = 6.3** .

For multiple estimates, the two extreme values can be utilized.

The Definition of Maximum Magnitude Earthquake

Possible ways to define

Some of the ways in which maximum magnitude have been defined are: (1) The largest possible earthquake that can occur given the current physical conditions (no change in the future) of the source area, or, (2) The largest possible earthquake to occur with a specified probability during a specified exposure time, or, (3) The largest earthquake likely to occur in a reasonable amount of time (life of facility involved ?). Note that (3) is a qualitative form of (2).

Possible synonyms

Maximum Possible Earthquake ; Maximum Credible Earthquake. The point here that these different terms can have various meanings to different individuals. The expression 'maximum magnitude earthquake' will be used herein and will be defined subsequently.

Problems

Given the long recurrence intervals for the larger intraplate earthquakes and the short historical record, there is the possibility that the "maximum" earthquake has not been recorded in a given zone. Poisson statistics would indicate that there is a 63% probability of an earthquake catalog containing an earthquake with recurrence interval equal to or greater than the length of the catalog. This suggests that, in more than one-third of the earthquake catalogs, there is likely to be an apparent deficiency of large shocks (Chinnery,1979). Another way to utilize Poisson statistics in this instance : In the southeastern U.S., the earthquake record is about 250 years long. There is a 1 in 5 chance (22%) that it contains a shock with a recurrence interval of 1000 years which has been suggested as a candidate definition for maximum magnitude.

Chinnery (1979) has demonstrated that there is no proof for an "absolute" upper bound to seismic moment, and hence earthquake size, on a global scale even though there are physical arguments that such an upper bound must exist. Thus, he points out that there is no unequivocal way to know with certainty if you have the maximum earthquake in a given catalog or not.

Definition for Maximum Magnitude for this Study.

The purpose of this study is to estimate the maximum magnitude earthquake for the Giles county, Virginia, seismic zone. Accordingly, we adopt a definition similar to (2) and (3) above. The "specified probability" will be set at 0.001, without consideration of exposure time. The question of whether or not such a seismic event can occur elsewhere in the area is not addressed.

The Estimation of Maximum Magnitude

Use of the Historical Record of Earthquakes

Recurrence relationships assume that the past record of small and large earthquakes is representative of future seismic activity for as long as is necessary. However, very long catalogs from seismically active interplate or plate marginal areas, e.g., the Middle East, China, and Japan, show long term changes in seismicity on time scales of 100's of years. Whether or not such secular variations are also appropriate for intraplate settings is not known for certain. Thus, the possibility exists that the largest earthquakes for a given seismic zone may be associated with a level of seismicity that is very different from the recent record there of smaller shocks.

The recurrence relation (Log N versus M) must be related to a maximum magnitude in some manner. If a physical limit or a "characteristic" earthquake does exist for a given zone, then the recurrence curve will have to cut-off abruptly or bend rapidly in some manner so as to be parallel to the ordinal axis at that magnitude. This factor impacts the simple extension of a magnitude recurrence curve to larger magnitudes in the maximum magnitude estimation process.

In terms of the maximum historical earthquake for the eastern U.S. host region, there were, e.g., the Ms > 8 shocks at New Madrid, Missouri, and the Ms > 7 shock at Charleston, South Carolina. Thus, at least two locations in the region have exhibited moderate to large earthquakes. New Madrid and Charleston are also the only seismic areas east of the Rocky Mountains that have paleoseismic evidence for pre-historical occurrences of larger shocks. There were 3 major earthquakes in the past 2000 years or less at New Madrid (Russ, 1979) and 3 moderate or larger shocks in the past 7200 years at Charleston (Obermier and others, 1987). When the recurrence curves for those areas (excluding the largest historical shocks) were projected to repeat times of some 600 years in Missouri and 1000 years in South Carolina, the magnitudes indicated were in good agreement with the estimated magnitudes for the largest historical earthquakes (Nuttli, 1981).

The agreement of historical and pre-historical data in Missouri and South Carolina is very important to the estimation of maximum magnitude earthquakes in the region as both shocks are large enough to be reasonable candidates for the maxima in their respective zones. Under the assumption that such is the case we have : (1) Different seismic zones in the eastern U.S. can have different maximum magnitude earthquakes, i.e., some zones have smaller maximum magnitudes than other zones, and, (2) The rate of strain accumulation, amount of fault surface, and the friction on the fault surfaces are different for different source volumes.

Magnitude Recurrence Relations for the Giles County Seismic Zone (GCSZ)

Bollinger and others (1989a) have recently completed an extensive study of frequency of earthquake occurrence in the southeastern U. S. That study included investigation of the Giles county, Virginia, seismic zone. Their results will be utilized in this study.

Specification of the Area of the GCSZ.

In some seismic hazard studies, it is necessary to normalize for the area (volume) being considered. Otherwise, there would be no limit (other than global) to how large a magnitude could be estimated as larger and larger source regions are considered (Nuttli,1981). However, the GCSZ is small enough (7,854 sq km (Davison, 1988 ; Bollinger and others, 1989a,b) that no normalization is required for the task at hand.

The definition of the actual boundaries of the seismic source zone is not without its own uncertainties, because most active sources tend to display a 'halo' of surrounding seismic activity. That activity is generally assumed to be due to peripheral stress perturbations induced by the zone proper. Such halos blur the actual boundaries of the principal zone, especially given errors in hypocentral locations. There is also the very real question as to whether or not the halo activity should be considered an integral part of the zone.

The GCSZ has the distinction of being the site for the second largest earthquake known to have occurred in the southeastern U.S. Its meizoseismal intensity was MMI VIII and Nuttli and others (1979, 1989) have estimated magnitudes of mb = 5.8 and Ms = 5.9. Its small meizoseismal area indicates an epicenter near the county seat of Pearisburg (Bollinger and Hopper, 1971). The spatial distribution of the historical seismicity (Bollinger, 1973a,b) shows the zone to be relatively isolated, but not sharply defined. The results from a decade of monitoring by a seismic network sited to study the zone have corroborated the principal historical results (Bollinger and others, 1986) that there is an area of isolated seismicity in the Giles county locale, but its spatial configuration is not simple (Bollinger and others, 1989b).

Fortunately, eight well constrained sets of focal mechanism solutions, based on both P-wave polarity and S/P wave amplitude ratios, have been developed for Giles county earthquakes (Munsey and Bollinger,1985 ; Davison,1988). Those focal mechanisms were used by Davison (1988) to estimate the regional in-situ stress as being compressive and northeasterly trending. Given that estimate, Davison (1988) was then able to select a preferred fault plane from each pair of nodal planes on the basis of compatibility between the direction of the slip on each nodal plane, as indicated by the focal mechanism, and the direction of slip expected from the regional stresses. Given the orthogonal relationship between the nodal plane pairs for each earthquake, slip compatibility with the regional stresses is an effective criterion. **Davison (1988) determined the average of the preferred nodal plane strikes to be N25°E.** It is important to note that this average strike estimate is based solely on focal mechanism data and is independent of any direct interpretation of epicentral patterns, the technique usually employed to identify earthquake fault zones.

The entire earthquake catalog for the GCSZ is shown in Figure 1 and listed in Appendix A. When the very poorly constrained epicenters for historical and recent shocks are deleted so as to leave only those whose hypocenters are known within ± 10 km, the pattern that remains is shown by Figure 2. Utilizing this data set (listed in Appendix B) in conjunction with the average strike of N25°E will allow the area (volume) of the GCSZ to be estimated. Figures 3 through 5 show the GCSZ definition based on a ±10 km width on either side of the N25°E trending line through the hypocentral lineation. That definition provides a geological interpretation of the seismic observational results.

<u>Use of Fault Plane Area - Magnitude Relationships</u>

The data bases for such relationships are almost entirely from interplate and plate-marginal regions that are very active seismically (high strain rates) and often exhibit surface faulting associated with the causal faults. The applicability of such results to a low activity, intraplate region containing only buried causal faults, some at relatively large depths, is questionable. The data bases themselves are not without some questions as to their adequacy and quality. However, the basic physics of the seismogenic process is contained in the spatial fault parameters and some of the fault areas were estimated with the help of aftershock surveys. They can, therefore, be used effectively as part of the maximum magnitude estimation procedure.

The physical theory of the earthquake process indicates that earthquake magnitude should be more strongly correlated with the logarithm of the fault area than with the logarithm of the fault length alone. Wyss (1979, 1980 ; Bonilla, 1980) and Singh and others (1980) have

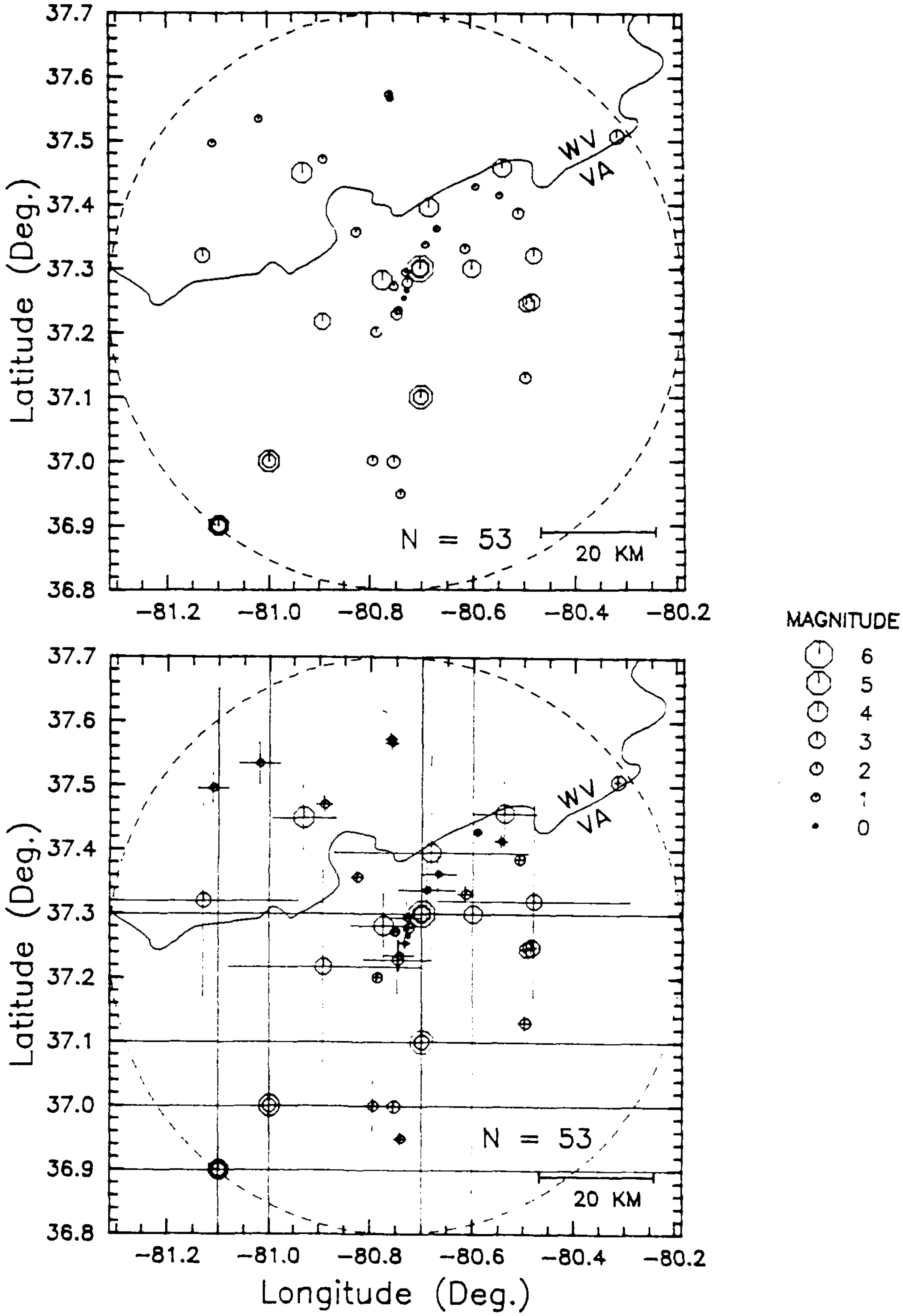


Figure 1. Seismicity Maps for the Giles county, Virginia, seismic zone - 1876 through 1988. Epicenters indicated by octagon symbols. Circular definition of zone (radius = 50 km) according to Davison, 1988. N = number of epicenters plotted. Upper figure : Epicenters only Lower figure : Same epicenters with horizontal error bars. The large error bars are for historical shocks for which instrumental control was lacking or sparse. The small error bars are the result of monitoring by a local network of seismographs (Bollinger et al. 1986).

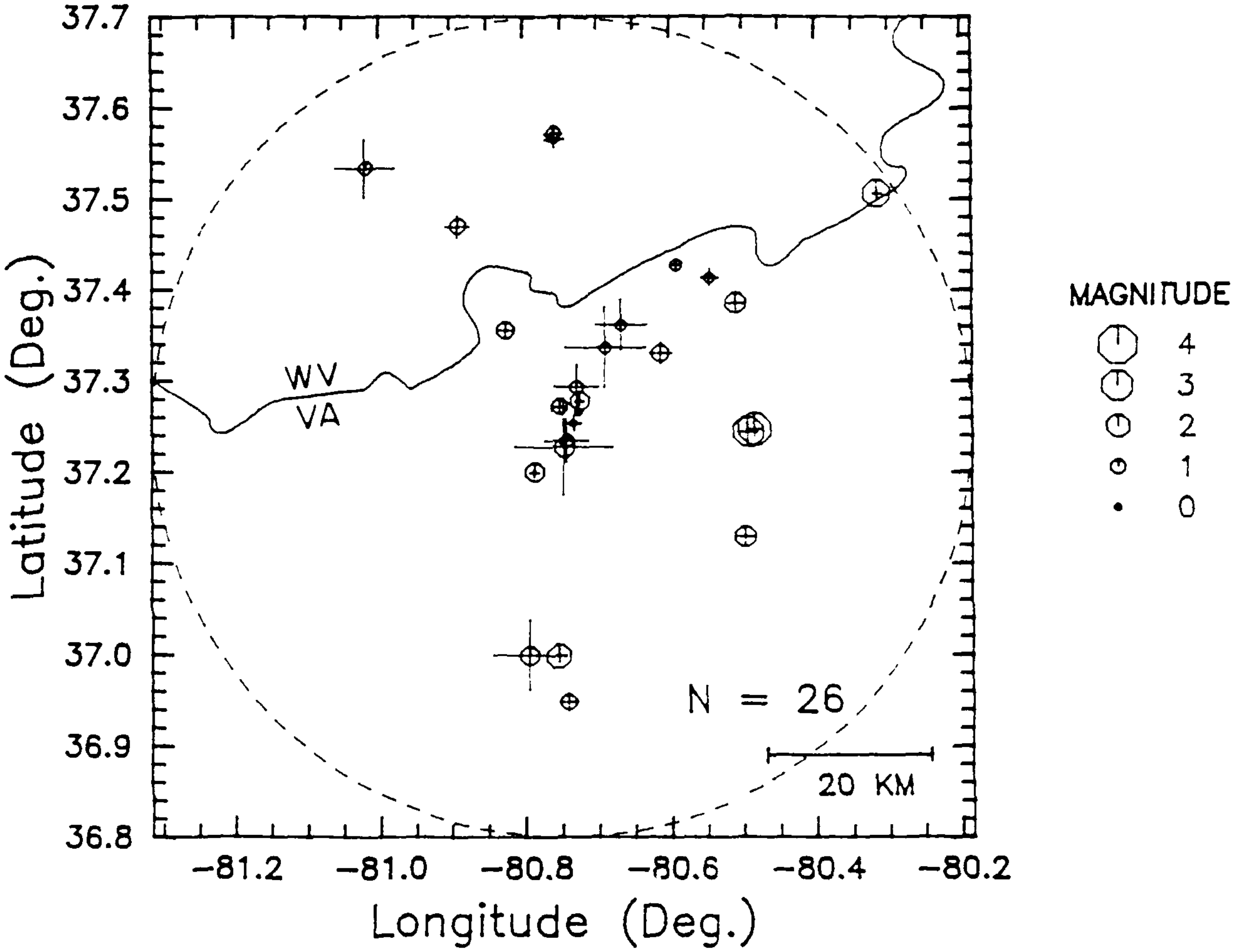
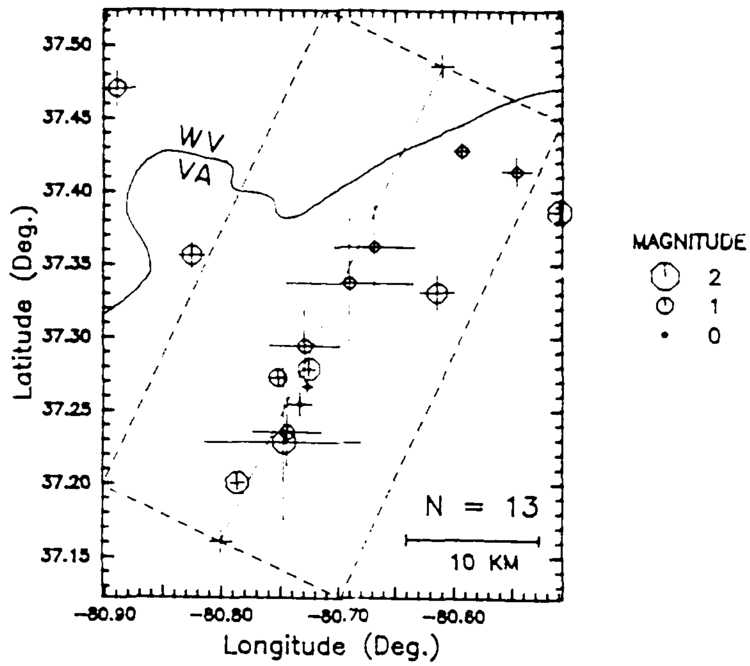


Figure 2. Seismicity Map for the Giles county, Virginia, seismic zone - 1876 through 1988 showing only those earthquakes for which the epicenters and focal depths are known withir ± 10 km. Symbols and format are the same as in Figure 1.



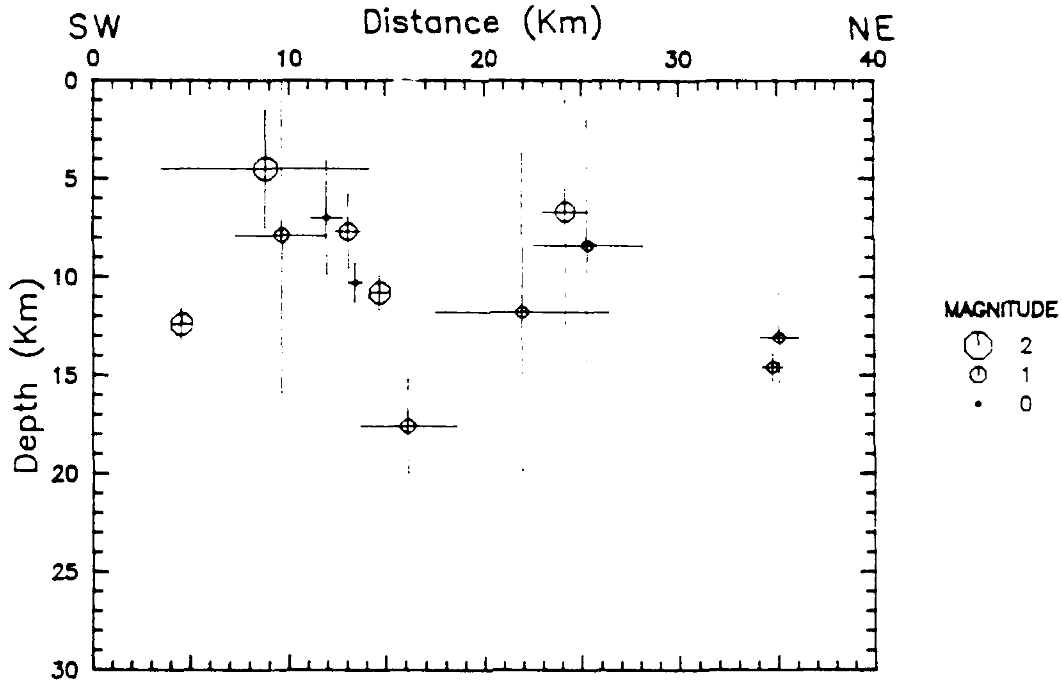


Figure 3. Tabular definition 'or the Giles county, Virginia, seismic zone. Epicenter and error bar symbols same as in Figure 1. Upper figure : Dashed box at ± 10 km about a line trending N25^{0}E encloses the zone proper ; Lower figure : Epicenters within the dashed box shown in the upper figure are projected into the vertical plane trending N25^{0}E shown here. Both horizontal and vertical error bars shown for each focus. Profile distance measured from southwest to northeast.

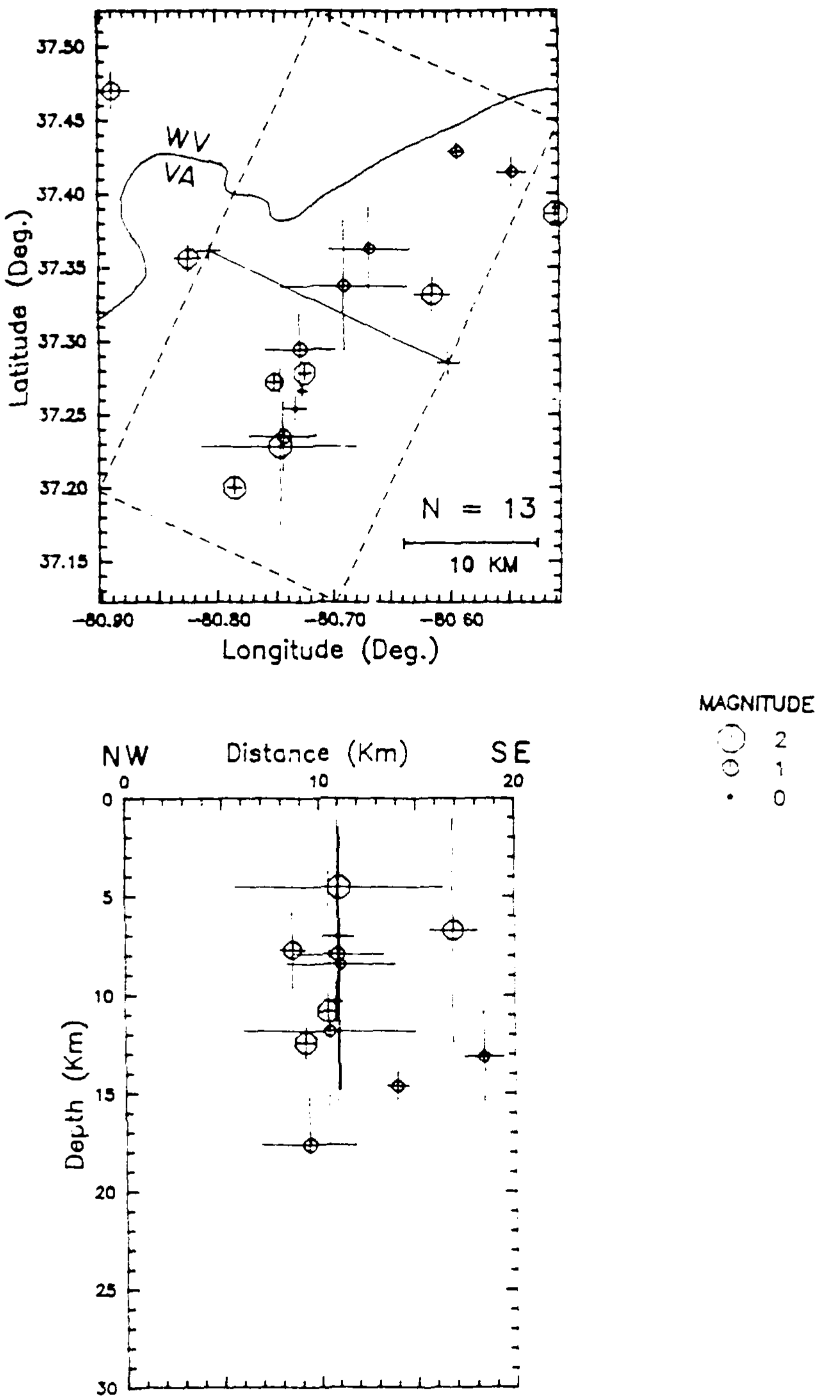


Figure 4. Tabular definition for the Giles county, Virginia, seismic zone. Epicenter and error bar symbols same as in Figure 1. Upper figure : Dashed box at ± 10 km about a line trending N25^{0}E encloses the zone proper ; Lower figure : Epicenters within the dashed box shown in the upper figure projected into the plane perpendicular to the N25^{0}E trend shown here. Both horizontal and vertical error bars shown for each focus. Profile distance measured from northwest to southeast.

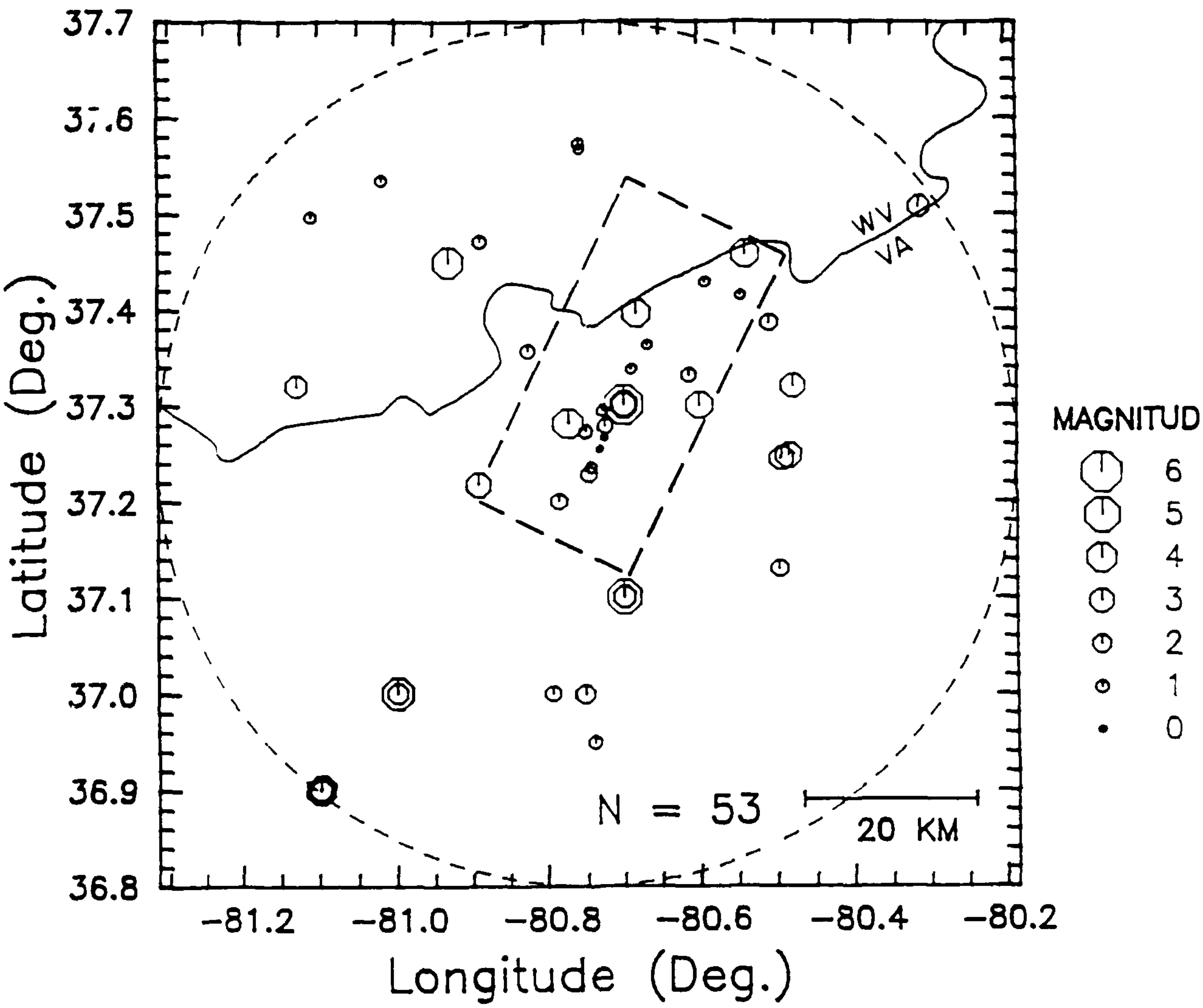


Figure 5. Seismicity map for the Giles county, Virginia, seismic zone - 1876 through 1988, showing all epicenters (octagon symbols) and the circular and rectangular definitions of the zone. The circular definition is a general one and includes the off-zone 'halo' events. The rectangular definition is for the zone proper and includes only those earthquakes thought to have originated within the principal seismogenic structure.

developed regressions of magnitude (M = mostly Ms with some M_L and M_w ; $M \geq 5.6$) with fault plane area (A, sq km) . Bonilla and others (1984) prefer the use of fault length (L) and/or displacement, but they also presented magnitude-fault area regressions. These equations are as follows :

Wyss (1979)	$M = 4.15 + 1.00 \text{ Log } A$
Singh et al. (1980)	$M = 4.53 + 0.89 \text{ Log } A$
Bonilla et al. (1984)	$M = 4.36 + 1.035 \text{ Log } A$

These expressions are similar to each other (they used similar data bases), and there is no obvious basis to prefer any one of them over the others and, thus, the average of their results will be employed herein. Furthermore, the M will be interpreted as Ms, because of the preponderance of that earthquake size measure in the input data bases. Bonilla and others (1984) magnitude - fault length expression, $M = 6.02 + 0.729 \text{ Log } L$, will be utilized only in a comparative manner as it relates primarily to surface ruptures.

Estimation Procedures and Results for the Giles County, Virginia Seismic Zone

The problems discussed in the preceding section must be dealt with by the analyst on a case by case basis. The decision must be made as to which techniques are applicable to the area being studied. Some problems, e.g., the fact that a global maximum earthquake has not yet been documented, can only be recognized. For other problems, e.g., the use of interplate magnitude-fault area relations in intraplate environments, it is necessary for the analyst to present the judgments and reasoning utilized to justify their use or non-use on the study area being considered.

Applications of Historical Seismicity

<u>Increment to the Historical Maximum Earthquake</u>

In practice, 0.5 or 1.0 magnitude units have been sometimes been added to the largest historical earthquake as an estimate of the maximum shock for a zone. This is a subjective procedure that depends completely on the judgment of the analyst. The only quantitative aspect of this procedure is the fact that such an addition actually implies an assumed lengthening of the historical record. Thus, for a b-value of -1, a 0.5 addition implies a 3.2 times lengthening of the historical record, while a 1.0 increment implies a factor of 10 times. Recognition of the actual amount of time extension should be made in each particular case.

Results for the GCSZ

For the GCSZ the b-value is 0.64 (Bollinger and others, 1989). Thus, an increment of 0.5 magnitude units implies a factor of 2.09X and a 1.0 increment a 4.37X factor. The earthquake catalog for the GCSZ is 215 years and those factors imply extension time intervals of 450 years and 940 years, respectively. As noted previously, the maximum shock for the zone was a Ms = 5.9. An increment of 1.0 Ms units is selected as both a conservative measure and as one that is compatible with the definition of maximum magnitude adopted herein. Thus, the estimation for this procedure is Ms = 6.9 which implies an extension time of 940 years.

Extrapolation of the Recurrence Curve

This procedure is similar to the preceding one except that the objective is a given recurrence interval, rather than a given magnitude increment. That is, the recurrence curve extrapolation results are directly dependent on the specific intercept (a) and slope (-b) values of the curve being extended. The magnitude increment addition is completely independent of the a and b values.

These extrapolations are usually linear, but it is well documented in the western U.S. that the difference between 'background seismicity' and large, 'characteristic earthquakes' is nonlinear. However, linear extrapolation is the most conservative with respect to the various truncated or exponential fall-off terminations proposed for log N versus M curves and will be employed herein.

Nuttli (1981) recommends use of the magnitude associated with a 1000 year recurrence interval (annual probability = 0.001) for seismic source zones (normalized to 30,000 (or less) sq km or 100,000 sq km) as an estimate of the maximum magnitude for eastern U.S. source zones. His recommendation is based on analyses of the Mew Madrid, Missouri and Charleston, South Carolina zones. In both of those zones, he deleted the largest historical earthquakes, determined a magnitude-recurrence relation for the remaining catalog, and then extrapolated the resulting Log N versus M curve to a recurrence interval of 1000 years. The magnitudes associated with the 1000 year intervals were in good agreement with those for the largest historical events that had been deleted. A problem with Nuttli's (1981) approach is that the recurrence relationships must be normalized to some arbitrary area to yield consistent results. Furthermore, its applicability to seismic zones with very small areas, such as the GCSZ, has not been demonstrated. Acknowledging those problems, we choose the 1000 year earthquake for the zone as a reasonable estimate of the GCSZ maximum magnitude shock.

Nuttli (1981) also noted that, "East of the Appalachians, the earthquake source zones are not so readily delineated, so it is difficult to assign maximum magnitude earthquakes to that part of the country." We agree with that assessment.

Results for the GCSZ

Bollinger and others (1989a) have determined the recurrence relationship for the GCSZ as,

$$\text{Log } Nc = 1.065 - 0.64\ mb(Lg).$$

That equation yields a mb(Lg) = 6.35 (ms = 6.95) for a recurrence interval of 1000 years. Bollinger and others (1989) note that interval estimates, at a specified confidence level, rather than point estimates, are the preferred manner for utilization of magnitude regression results. However, in this instance, a point estimate is required by the curve extension procedure.

Thus, the maximum magnitude derived from this technique is :

Ms = 6.95.

Here, mb(Lg) has been taken as equal to mb and the Nuttli and others (1989) mb to Ms conversion has been used

Other Statistical Approaches

These approaches make use of extreme-value theory (see, e.g., Yegulalp and Kuo, 1974 or Kijko, 1984). That theory assumes that the occurrence of maximum earthquakes within a given interval of time is a random event and that maximum earthquakes in the future will occur in the same way as those in the past. In principle, this sounds ideally suited to the task at hand. However, in applications to date, it appears that very large, high quality data sets are required for useful results (Coppersmith and others,1987). Knopoff and Kagan (1977) studied synthetic data sets to show that unacceptably large errors could result from extreme-value techniques with data bases similar to those often encountered in practice.

McGuire (1977) investigated the use of the sparse data sets available for the eastern U.S. to estimate the maximum earthquake by means of maximum-likelihood techniques. He concluded that the data were inadequate to define with any confidence the maximum possible earthquake for a given seismic zone. Bender (1988) extended McGuire's conclusion to state that, for most real data sets, the amount of information available is too small to permit a reliable estimate of maximum magnitude to be obtained, regardless of the technique used. Accordingly, this class of estimation procedures will not be applied in this study.

Applications of Fault Zone Dimensions

Magnitude versus Fault Area Results for the GCSZ

The earthquake foci within ± 10 km of a plane trending N25°W are assumed to be in the GCSZ and they will be used to estimate the spatial dimensions of the causal geologic fault zone structure (Bollinger and others, 1989b). The bases for that assumption are : (1) The N25°W trend is the approximate strike of the causal fault zone, (2) The dip of the zone is steep, but not necessarily vertical, and, (3) The actual errors in the hypocentral locations may be somewhat larger than estimated. That estimate is assumed to be for the same geologic structure that was involved in the 1897 earthquake sequence, including its Ms 5.9 mainshock, as well as the subsequent seismic activity in the Giles county locale up to the present time.

It is important to note that, within the past 20 years, the 'off zone' activity (Figure 1) has included shocks of up to a mb of 4.6 That fact is seen as being compatible with the spatial stress perturbations induced into the volume surrounding a seismic zone capable of generating a Ms 6 or larger earthquake.

The areal extent of the GCSZ is described by a small number (13) of accurately located microearthquake foci. They are judged to be sufficient to estimate a range for the fault area by means of a maximum-minimum type of approach that incorporates different assumptions on the shape of the zone. Specifically, six different areas will be derived from the following :

* Two different horizontal lengths, 20 km and 30 km,
* Three different vertical extents, 8 km, 10 km and 13 km, and
* One rectangular shape and two polygonal shapes.

The different horizontal and vertical dimensions and the different configurations are necessitated by the inclusion or exclusion of peripheral foci for the purpose of estimating areal maxima and minima (see Figure 6 and 7 ; Bollinger and others, 1989b). These 6 areas will now be used to determine 6 magnitudes whose mean value will comprise the maximum magnitude estimate for this technique.

Rectangular Fault Shape : The vertical section (Figure 6) shows that the well-constrained focal depths in the zone vary from about 5 km to about 15 km. The horizontal extent is for lengths of approximately 20 km or 30 km depending on whether or not the two most northeasterly foci. at approximately 15 km depth, are included or not. Assuming a simple rectangular shape from these approximate dimensions yields areas of 200 sq km or 300 sq. km. These areas, in turn, imply Ms values of 6.59 and 6.76 respectively.

Polygonal Fault Shapes : Instead of using the spatial distribution of foci as a general guide as was done in the preceding, they can also be employed as the actual periphery of the zone. For that senario, the

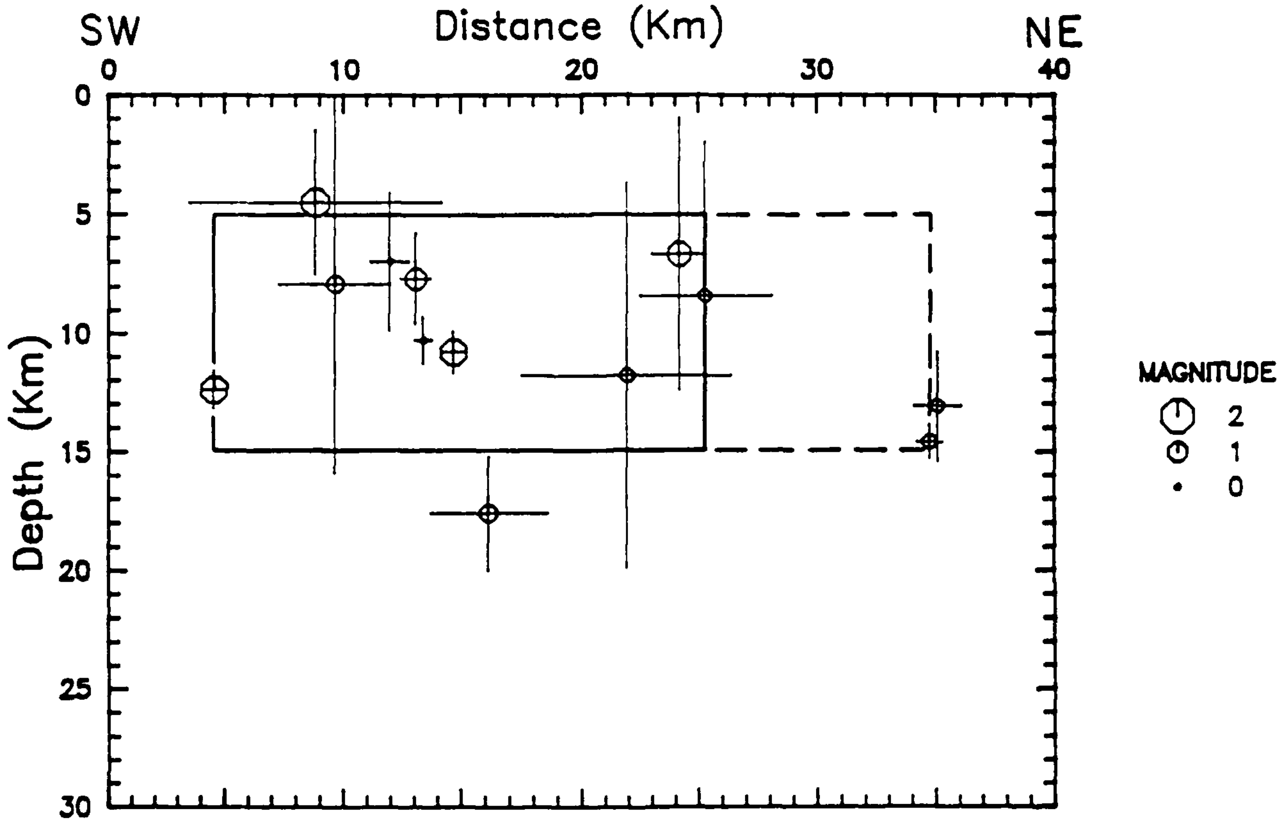


Figure 6. Definition of rectangular fault plane areas for the Giles county, Virginia seismic zone. The smaller zone has an area of 200 sq km and the larger area is 300 sq km. km.

outermost hypocenters are connected by straight lines and the enclosed area measured. In this instance, that procedure allows for three different vertical dimension values that differ principally depending on whether or not the single deep focus at 18 km is included or not (Figure 7). The resultings areas are 112, 157, 190, and 253 sq km. The derived Ms estimates are 6.34, 6.48, 6.57 and 6.69 respectively.

The average of the preceding six estimates is :

Ms = 6.57,

and that value serves as the maximum magnitude estimate for this procedure.

Bonilla and others' (1984) Magnitude versus Fault Length relationship yields Ms = 6.96 for L = 20 km and Ms = 7.10 for L = 30 km. It is interesting to note that these values are closer to those from the incremental methods than the average from the areal method.

Strain rate or Rate of Moment Release Methods

These techniques have been developed in seismically active, interplate regions, such as California, where the active faults are available for geologic study by surface methods and the strain rates are high enough to be measurable by geodetic and seismic means. Such conditions and data bases are not available for the eastern U.S. and, thus, this class of methods cannot be brought to bear on the problem at hand.

Reference to a Global Data Base

The rationale here is to substitute space for time in an attempt to overcome a short historical record as in the EPRI study by Coppersmith and others (1987). Their results can be employed as a qualitative tool to assist in the estimation of maximum earthquakes. Those results to date are :

1) Only 5 great earthquakes (M>8) and some 20 shocks larger than Ms

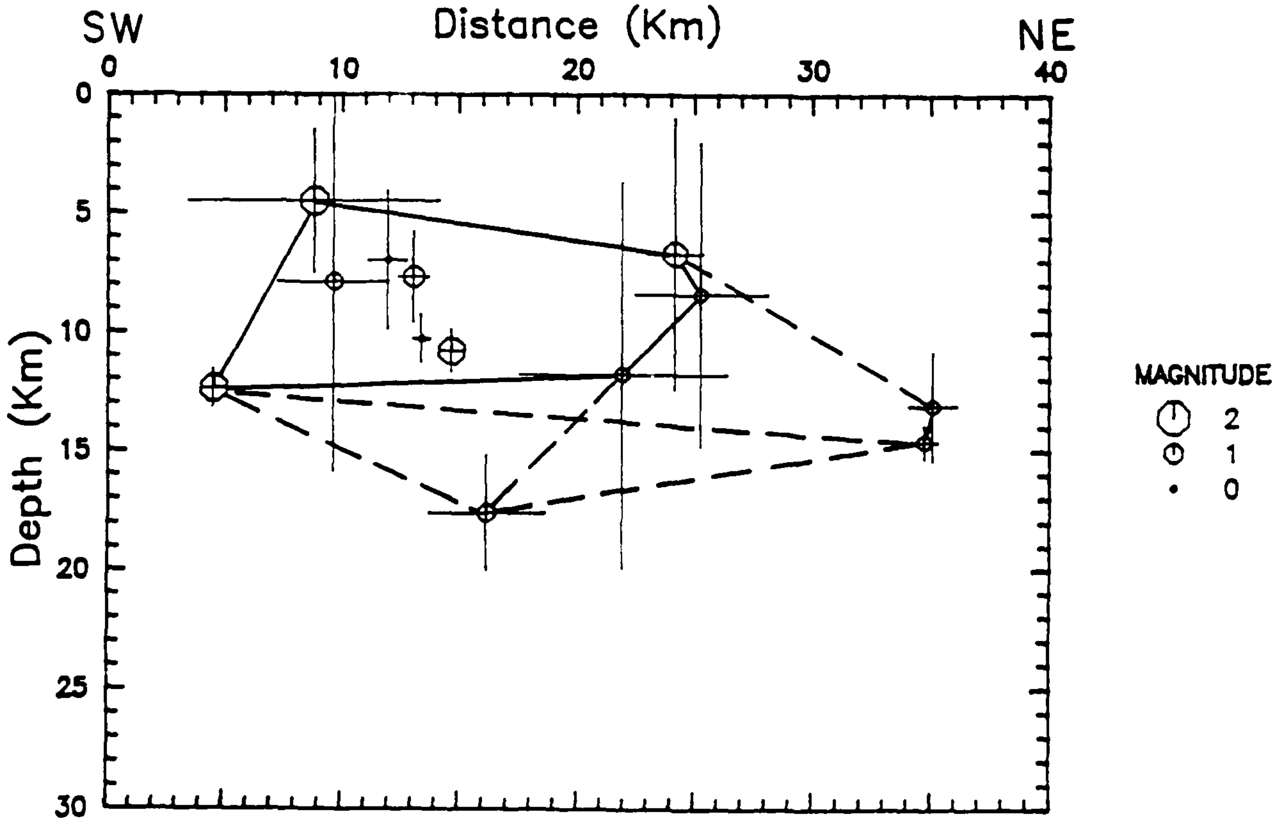


Figure 7. Definition of polygonal fault areas. The smaller areas are 112 and 157 sq km and the larger areas are 190 and 253 sq km.

7 worldwide in intraplate regions during historical time,

2) Most of those earthquakes (68%) are at locations of prior seismicity.

3) Paleozoic crust is far more active crustal age province compared to Precambrian crust, and,

4) The horizontal deviatoric stress is compressive in 86% of the cases.

Unfortunately, at its present state of development, this technique is not suitable for application to the problem at hand.

Summary

Three estimates for the maximum magnitude associated with the Giles county, Virginia, seismic zone have been developed. Those estimates and the techniques employed to obtain them are :

Ms = 6.9, from adding an increment to the maximum historical earthquake in the zone,

Ms = 6.95, from extension of the magnitude recurrence curve for the zone, and

Ms = 6.57, from estimates of the area of the zone.

These values are to be given equal weight and can be employed in a number of ways. If a single value is required, then the average, rounded to the nearest one-tenth, should be used. That value is :

Ms = 6.8 .

The mb equivalent is 6.3. If multiple values can be accommodated the two extreme values can be utilized.

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APPENDIX A.

Earthquake Catalog for the Giles County, Virginia, Seismic Zone -

All earthquakes : 1876 through 1988

within

A circle of radius 50 km centered at 37.25° - 80.75°

13-FEB-89 14:19:30 for the program RWGEN
Input data from file .... : GCO.GEN

Lab	Date YearMoDy	OT (UCT) HrMnSec	Hypocenter Lat	Lon	Depth	Error (km) ERH	ERZ	Sr	Magnitudes Mag1	Mag2	Mag3	Int S
VA	18761221	1530	36.9 N	81.1 W		83.4		HG	2.4			2G
VA	18790901	12	36.9 N	81.1 W		83.4		HG	2.4			2G
VA	18850202	1210	36.9 N	81.1 W		83.4		HG	3.3			4G
VA	18970503	1718	37.1 N	80.7 W		83.4		HG	5.0			7G
VA	18970503	19	37.1 N	80.7 W		83.4		HG	2.7			3G
VA	18970503	2110	37.1 N	80.7 W		83.4		HG	2.7			3G
VA	18970503	23	37.1 N	80.7 W		83.4		HG	2.7			3G
VA	18970531	1858	37.3 N	80.7 W		83.4		HG	5.8	5.8FG		8G
VA	18970629	03	37.3 N	80.7 W		83.4		HG	3.7			4G
VA	18970904	11	36.9 N	81.1 W		83.4		HG	2.7			3G
VA	18971022	0320	36.9 N	81.1 W		83.4		HG	4.1			5G
VA	18980205	20	37.0 N	81.0 W		83.4		HG	4.5			6G
VA	18980206	02	37.0 N	81.0 W		83.4		HG	2.4			2G
VA	18981125	20	37.0 N	81.0 W		83.4		HG	4.6	4.6FG		5G
VA	18990213	0930	37.0 N	81.0 W		83.4		HG	4.4			5G
VA	19020518	04	37.3 N	80.6 W		83.4		HG	3.5			5G
VA	19170419		37.0 N	81.0 W		222.4		HG	2.4			2G
VA	19590423	205839.5	37.395N	80.682W	1.0	16.7		IG	3.8	3.8FG		6G
VA	19590707	2317	37.3 N	80.7 W		27.8		HG	3.0			4G
VA	19590821	1720	37.3 N	80.7 W		27.8		HG	3.1			4G
VA	19680308	053815.7	37.281N	80.774W	8.0	5.6		IG	3.9PG	4.1NG		4G
WV	19691120	010009.3	37.449N	80.932W	3.0	5.6		IG	4.3PG	4.6NG		6G
VA	19740530	212835.3	37.457N	80.540W	5.0	5.6		IG	3.7	3.7MG		5G
VA	19750307	124513.5	37.32 N	80.48 W	5.0	16.7		IG	3.0	3.0NG		2G
VA	19751111	081037.6	37.217N	80.892W	1.0	16.7		IG	3.2	3.2NG		6G
WV	19760703	205345.8	37.32 N	81.13 W	1.0	16.7		IG	2.7	2.7NG		
VA	19780128	231323.4	37.228N	80.747W	4.5	5.9	3.0	IV	1.6	1.6DV		
VA	19780510	041910.9	37.294N	80.729W	17.6	2.7	2.4	IV	0.8	0.8DV		
VA	19780525	083025.1	37.000N	80.794W	12.1	4.3	3.8	IV	1.5	1.5DV		
VA	19780728	083940.7	37.337N	80.690W	11.8	4.9	8.1	IV	0.6	0.6DV		
VA	19780830	021938.2	37.362N	80.668W	8.4	3.1	6.4	IV	0.5	0.5DV		
VA	19800218	035855.2	37.428N	80.593W	14.6	0.6	0.7	IV	0.6	0.6DV		
WV	19800410	223315.5	37.496N	81.111W	0.2	2.6	99.0	IV	0.8	0.8DV		
VA	19801202	074738.2	37.414N	80.546W	13.1	1.1	2.3	IV	0.5	0.5DV		
VA	19810824	115011.4	36.949N	80.742W	16.1	1.1	1.6	IV	1.1	1.1DV		
VA	19811112	062414.1	37.235N	80.744W	7.9	2.6	3.0	IV	0.8	0.8DV		
VA	19811204	023556.5	36.999N	80.754W	5.9	0.8	1.2	IV	2.1	2.1DV		
VA	19820518	031633.8	37.130N	80.497W	11.0	1.2	1.3	IV	1.7	1.7DV		
VA	19830108	155355.9	37.331N	80.614W	6.7	1.3	5.7	IV	1.3	1.3DV		
VA	19830125	203858.0	37.386N	80.509W	16.8	0.8	1.8	IV	1.7	1.7DV		
VA	19830420	180956.4	37.356N	80.825W	11.5	1.0	1.2	IV	1.3	1.3DV		
VA	19830517	020247.6	37.254N	80.733W	7.0	0.9	2.9	IV	0.0	0.0DV		
WV	19830526	010444.9	37.507N	80.315W	8.6	0.5	1.1	IV	2.6NV	1.9DV		
VA	19830710	140539.5	37.272N	80.752W	7.7	0.7	1.9	IV	1.1	1.1DV		
WV	19831113	165106.6	37.566N	80.759W	11.8	1.1	2.1	IV	0.5	0.5DV		
WV	19831113	175049.8	37.572N	80.760W	14.2	1.0	1.3	IV	0.8	0.8DV		
VA	19831209	001158.0	37.200N	80.786W	12.4	0.5	0.8	IV	1.5	1.5DV		
WV	19840311	040139.0	37.470N	80.890W	1.1	1.4	4.8	IV	1.1	1.1DV		
VA	19840702	195138.6	37.278N	80.725W	10.8	0.5	0.9	IV	1.5	1.5DV		
VA	19841117	031728.3	37.266N	80.727W	10.3	0.4	1.0	IV	0.0	0.0DV		

There have been 50 events listed so far.

Lab	Date YearMoDy	OT (UCT) HrMnSec	Hypocenter Lat	Lon	Depth	Error (km) ERH	ERZ	Sr	Mag1	Magnitudes Mag2	Mag3	Int S
VA	19850610	122238.3	37.248N	80.485W	11.1	0.9	2.0	IV	3.2NV	2.8DV		4V
WV	19850614	075710.2	37.534N	81.020W	2.4	3.6	4.4	IV	0.8	0.8DV		
VA	19860326	163623.9	37.245N	80.494W	11.9	1.1	2.4	IV	2.9	2.9DV		4V

There are 53 events in this listing.

SOURCE CODES:

B - Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
E - Earth Physics Branch, Canadian catalog,
G - USGS - State Seismicity Maps (Stover/Reagor et al.),
I - EPRI Catalog (8 July 1986),
N - Neilsen, 1982 (Stanford Data Base...),
R - Barstow et al., 1981 (Rondout Asso.), NUREG/CR-1577,
S - Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
T - Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
U - Earthquake History of the U.S./U.S. Earthquakes,
V - SEUSSN Bulletins (Va. Tech Publication),
Y - Felt area only; value is the average of those found in G and R above,
Z - Felt area only; value is the average of those found in U and R above,

LOCATION CODES:

H - Historical Location (from intensity/felt area data),
I - Instrumental Location,

MAGNITUDE CODES:

B - mb from Baysian estimate (Veneziano & VanDyck, 1984),
C - mb from intensity and felt area (Sibol et al., 1987)
D - Md from duration or coda length,
F - mb from felt area/attenuation data,
I - mb from intensity data
L - ML (Richter, 1958),
M - mb determined from modified instruments/formuli,
N - mb from Lg wave data (Nuttli, 1973),
O - m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
P - mb from P wave data (Gutenberg and Richter, 1956),
S - MS (Bath, 1966; Gutenberg, 1945),
X - Magnitude of unknown type.

APPENDIX B.

Earthquake Catalog for the Giles County, Virginia, Seismic Zone -

All earthquakes whose hypocentral error estimates are $\leq \pm 10$ km

and

whose epicenters are within a rectangle oriented N25°E

with dimensions of 20 km by 41 km.

13-FEB-89 14:19:52 for the program RWGEN
Input data from file ......: GCOSMALL.GEN

Lab	Date YearMoDy	OT (UCT) HrMnSec	Hypocenter Lat	Lon	Depth	Error (km) ERH	ERZ	Sr	Magnitudes Mag1	Mag2	Mag3	Int S
VA	19780128	231323.4	37.228N	80.747W	4.5	5.9	3.0	IV	1.6	1.6DV		
VA	19780510	041910.9	37.294N	80.729W	17.6	2.7	2.4	IV	0.8	0.8DV		
VA	19780728	083940.7	37.337N	80.690W	11.8	4.9	8.1	IV	0.6	0.6DV		
VA	19780830	021938.2	37.362N	80.668W	8.4	3.1	6.4	IV	0.5	0.5DV		
VA	19800218	035855.2	37.428N	80.593W	14.6	0.6	0.7	IV	0.6	0.6DV		
VA	19801202	074738.2	37.414N	80.546W	13.1	1.1	2.3	IV	0.5	0.5DV		
VA	19811112	062414.1	37.235N	80.744W	7.9	2.6	8.0	IV	0.8	0.8DV		
VA	19830108	155355.9	37.331N	80.614W	6.7	1.3	5.7	IV	1.3	1.3DV		
VA	19830517	020247.6	37.254N	80.733W	7.0	0.9	2.9	IV	0.0	0.0DV		
VA	19830710	140539.5	37.272N	80.752W	7.7	0.7	1.9	IV	1.1	1.1DV		
VA	19831209	001158.0	37.200N	80.786W	12.4	0.5	0.8	IV	1.5	1.5DV		
VA	19840702	195138.6	37.278N	80.725W	10.8	0.5	0.9	IV	1.5	1.5DV		
VA	19841117	031728.3	37.266N	80.727W	10.3	0.4	1.0	IV	0.0	0.0DV		

There are 13 events in this listing.

SOURCE CODES:
B - Bollinger, 1975, Southeastern U. S. Catalog 1754-1974,
E - Earth Physics Branch, Canadian catalog,
G - USGS - State Seismicity Maps (Stover/Reagor et al.),
I - EPRI Catalog (8 July 1986),
N - Neilsen, 1982 (Stanford Data Base...),
R - Barstow et al., 1981 (Rondout Asso.), NUREG/CR-1577,
S - Street and Turcotte, 1977, BSSA, 67, pp. 599-614,
T - Reinbold and Johnston (TEIC), 1986, USGS Final Rept.,
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V - SEUSSN Bulletins (Va. Tech Publication),
Y - Felt area only; value is the average of those found in G and R above,
Z - Felt area only; value is the average of those found in U and R above,

LOCATION CODES:
H - Historical Location (from intensity/felt area data),
I - Instrumental Location,

MAGNITUDE CODES:
B - mb from Baysian estimate (Veneziano & VanDyck, 1984),
C - mb from intensity and felt area (Sibol et al., 1987)
D - Md from duration or coda length,
F - mb from felt area/attenuation data,
I - mb from intensity data
L - ML (Richter, 1958),
M - mb determined from modified instruments/formuli,
N - mb from Lg wave data (Nuttli, 1973),
O - m3Hz (Lawson, et al., 1979 - Oklahoma earthquakes),
P - mb from P wave data (Gutenberg and Richter, 1956),
S - MS (Bath, 1966; Gutenberg, 1945),
X - Magnitude of unknown type.

APPENDIX F:

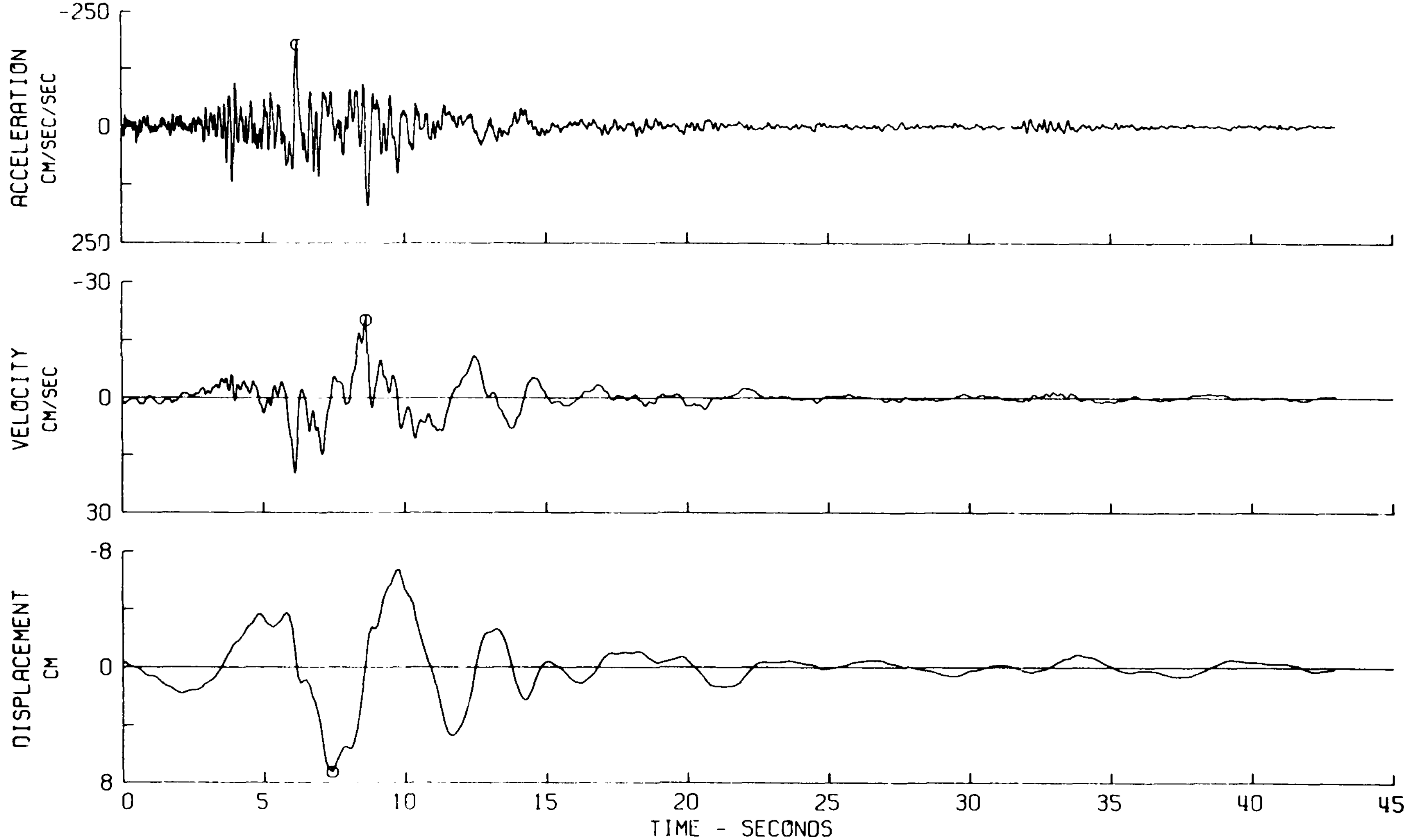
RECOMMENDED ACCELEROGRAMS AND RESPONSE SPECTRA

From California Institute of Technology,
Strong Motion Earthquake Catalogue, 1971 to 1975

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

I10198 71.069.0 GRIFFITH PARK OBSERVATORY, MOON ROOM, LOS ANGELES, CAL. COMP S00W

⊙ PEAK VALUES : ACCEL = -176.9 CM/SEC/SEC VELOCITY = -20.2 CM/SEC DISPL = 7.3 CM

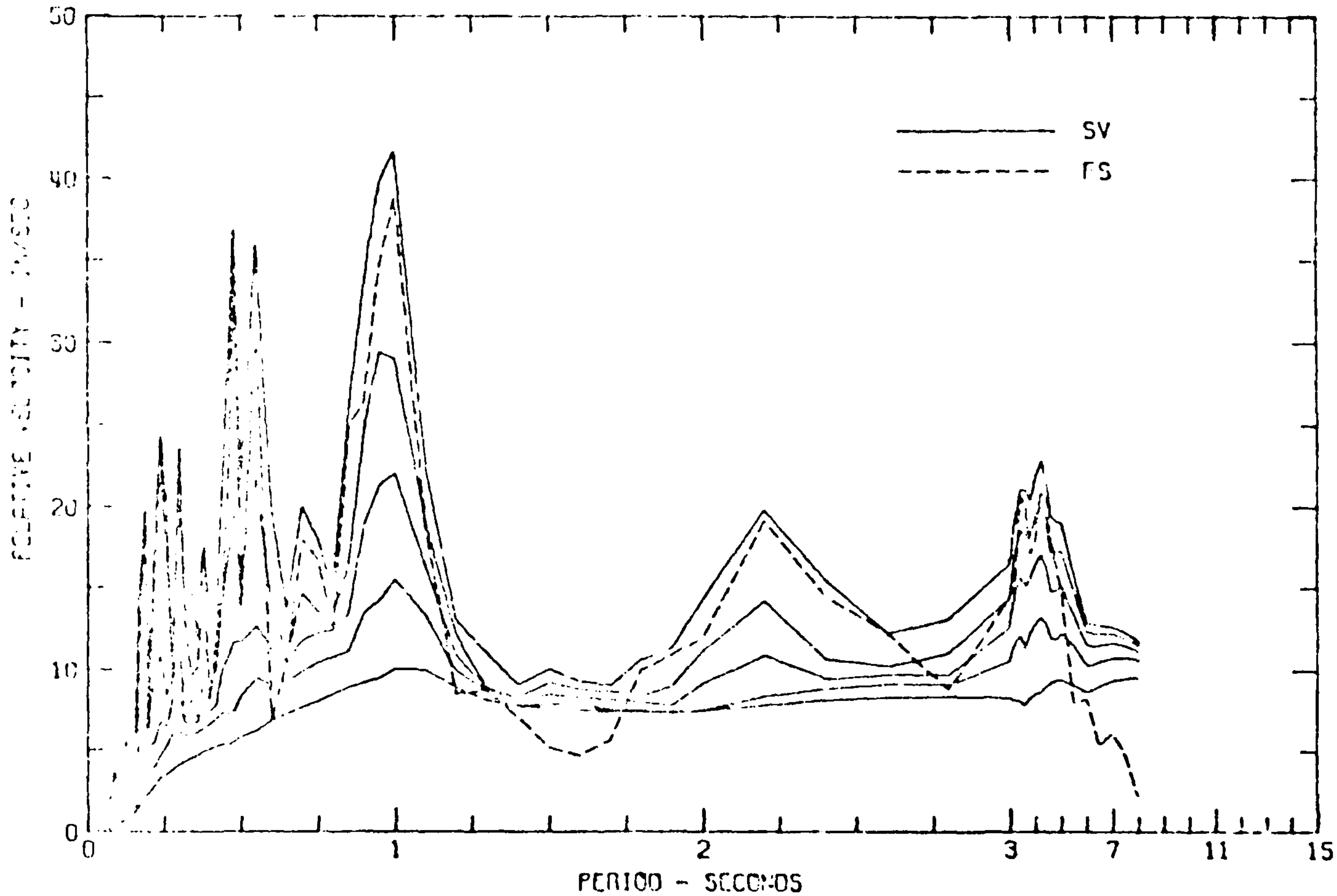


RELATIVE VELOCITY RESPONSE SPECTRUM

SAN FERNANDO EARTHQUAKE FEB 9. 1971 - 0600 PST

III0195 71.063.0 GRIFFITH PARK OBSERVATORY, MOON ROOM, LOS ANGELES, CAL. COMP S00W

DAMPING VALUES ARE 0. 2. 5. 10 AND 20 PERCENT OF CRITICAL

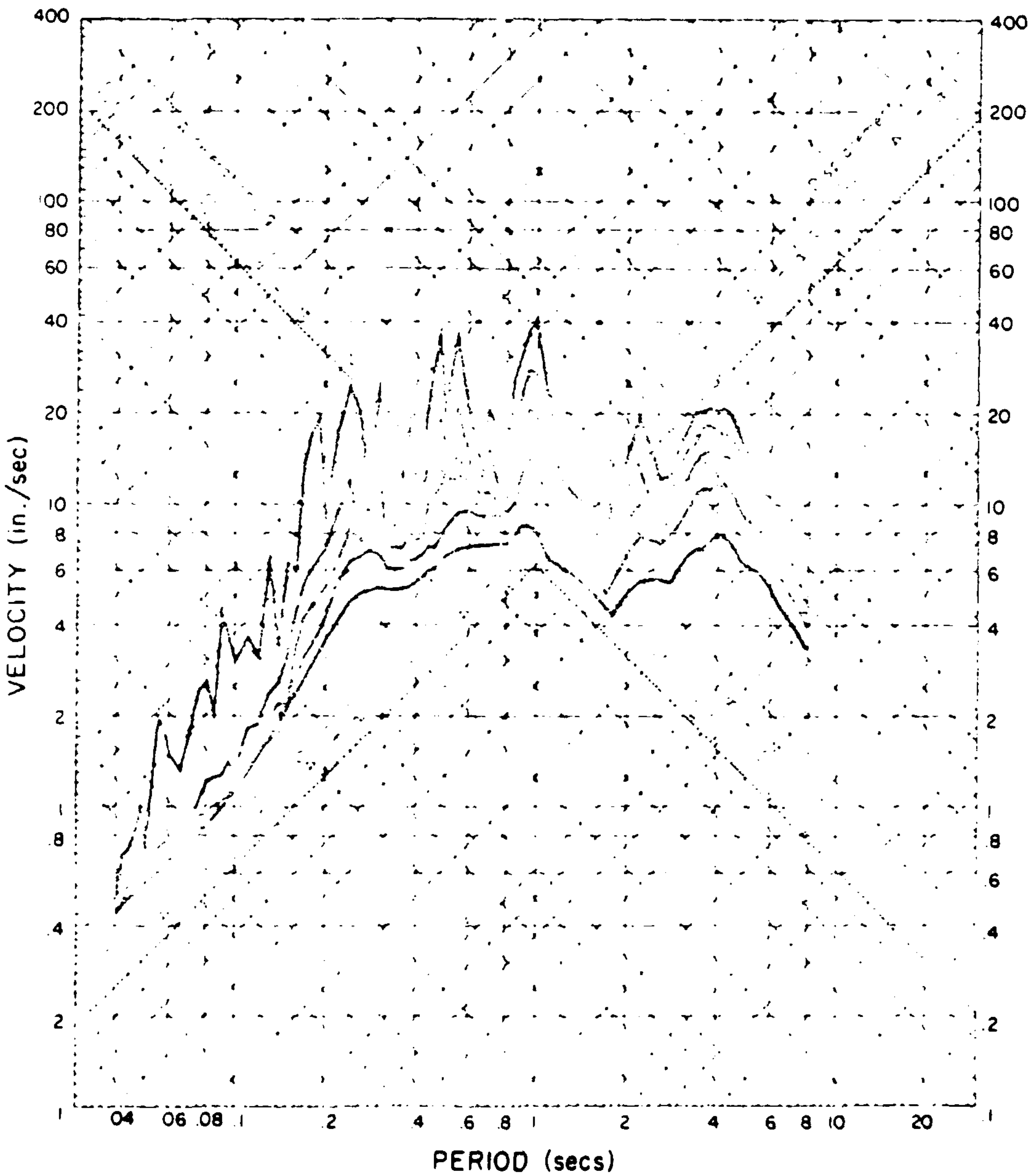


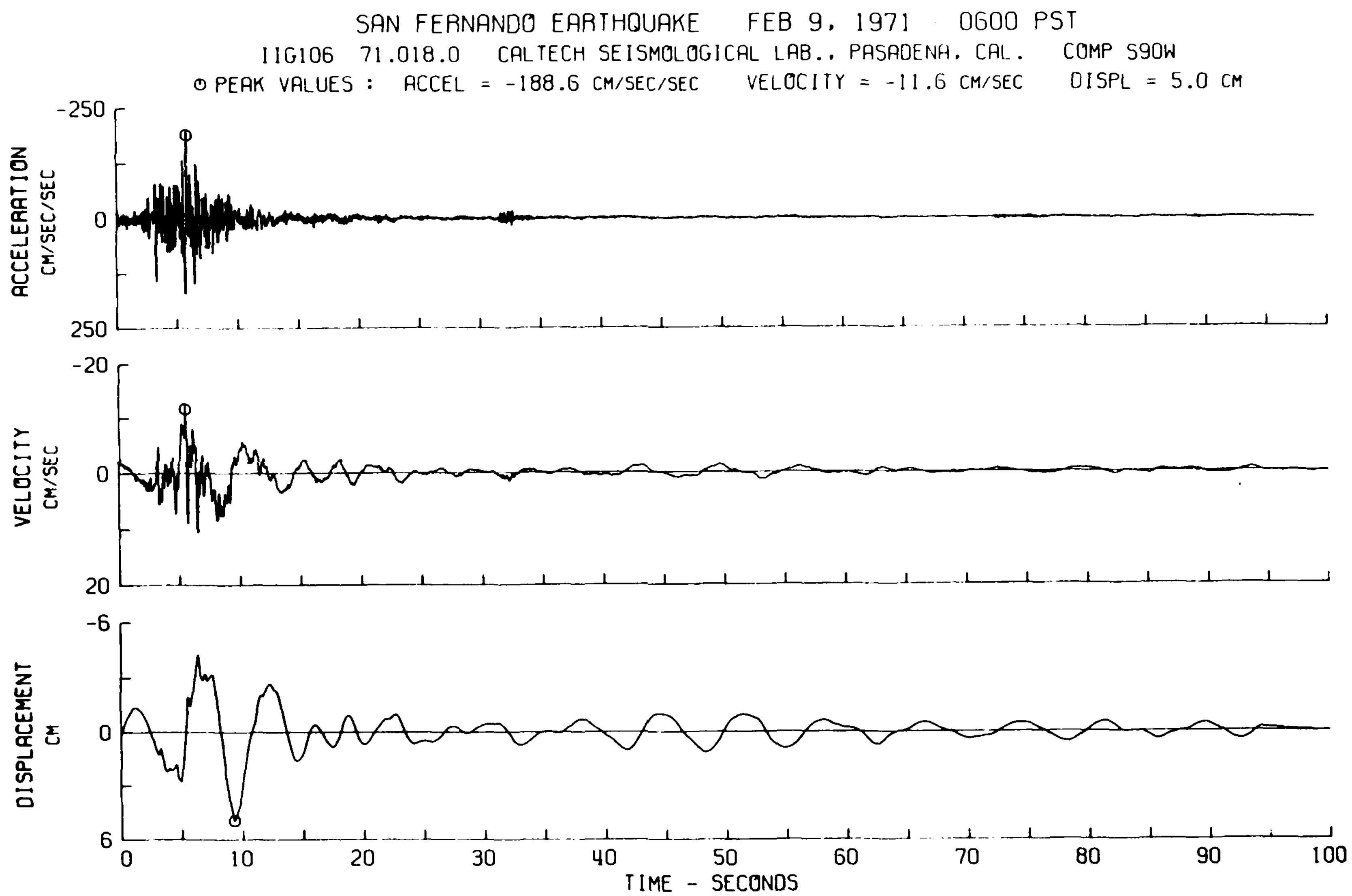
RESPONSE SPECTRUM

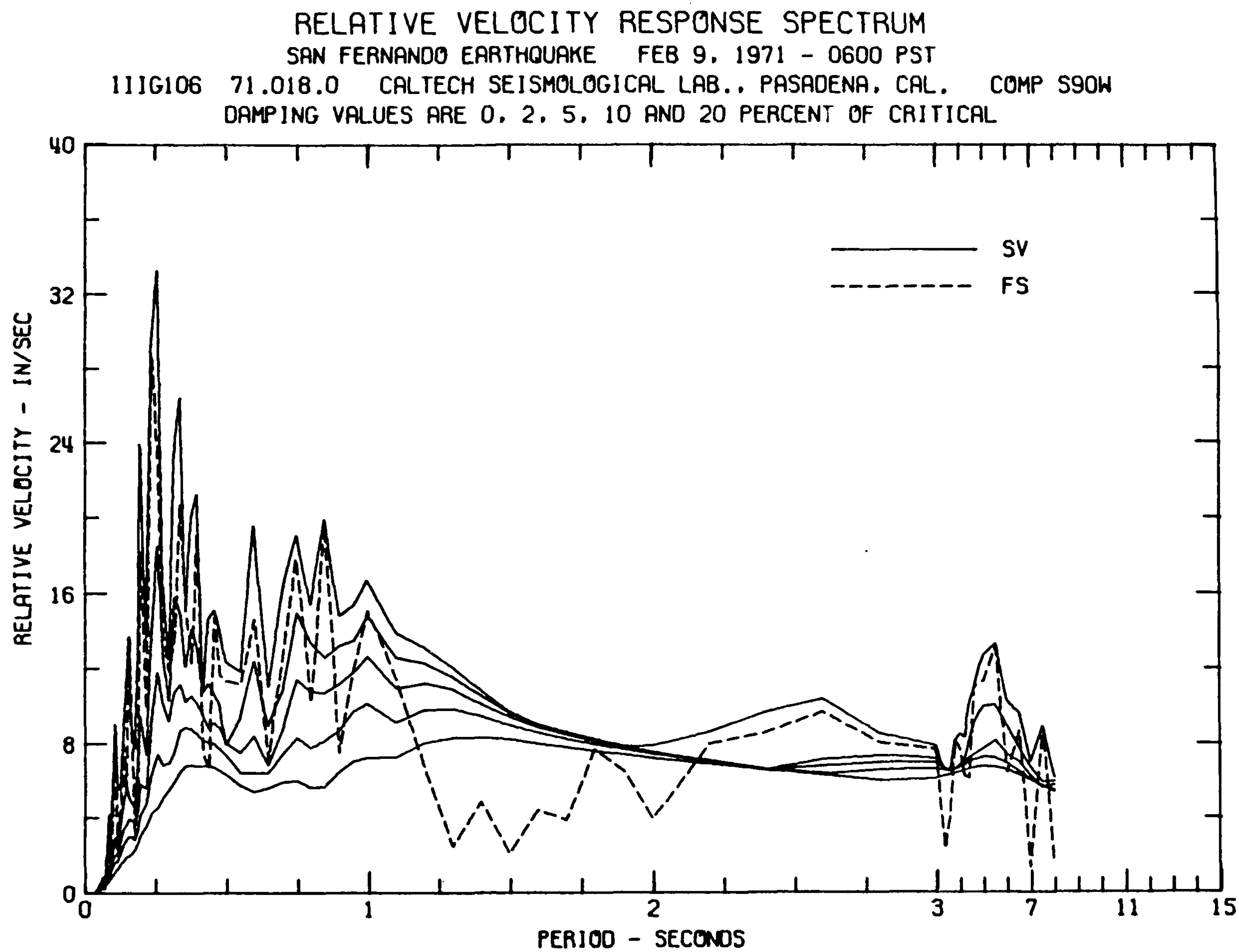
SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

III?198 71.039.0 GRIFFITH PARK OBSERVATORY, MOON ROOM, LOS ANGELES, CAL. COMP S00W

DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL




SAN FERNANDO EARTHQUAKE FEB 9, 1971 0600 PST
IIG106 71.018.0 CALTECH SEISMOLOGICAL LAB., PASADENA, CAL. COMP S90W
⊙ PEAK VALUES : ACCEL = -188.6 CM/SEC/SEC VELOCITY = -11.6 CM/SEC DISPL = 5.0 CM
ACCELERATION
CM/SEC/SEC
-250
0
250
VELOCITY
CM/SEC
-20
0
20
DISPLACEMENT
CM
-6
0
6
0
10
20
30
40
50
60
70
80
90
100
TIME - SECONDS

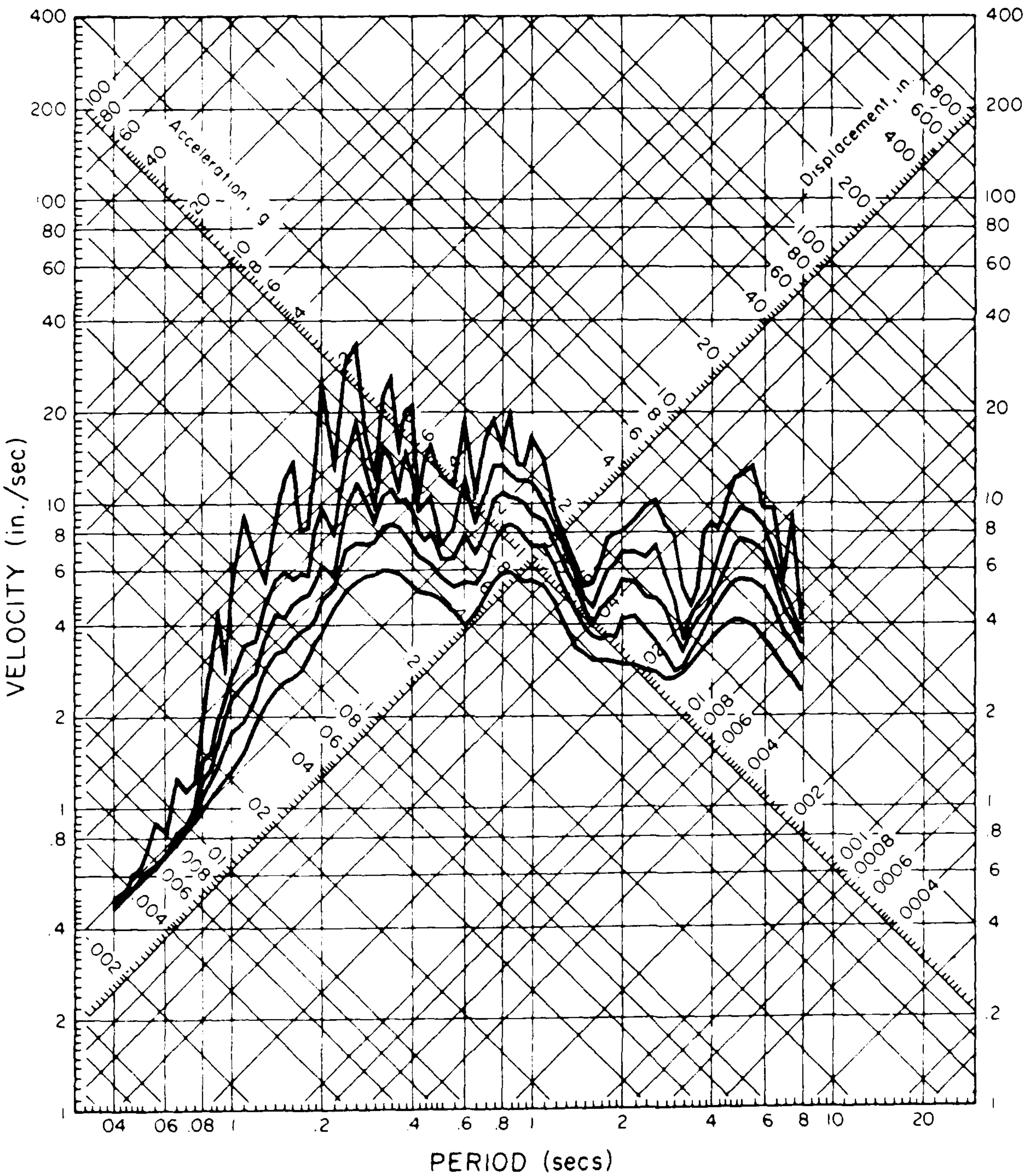

RELATIVE VELOCITY RESPONSE SPECTRUM
SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST
IIIG106 71.018.0 CALTECH SEISMOLOGICAL LAB., PASADENA, CAL. COMP S90W
DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL
SV
FS
RELATIVE VELOCITY - IN/SEC
PERIOD - SECONDS
0
8
16
24
32
40
1
2
3
7
11
15

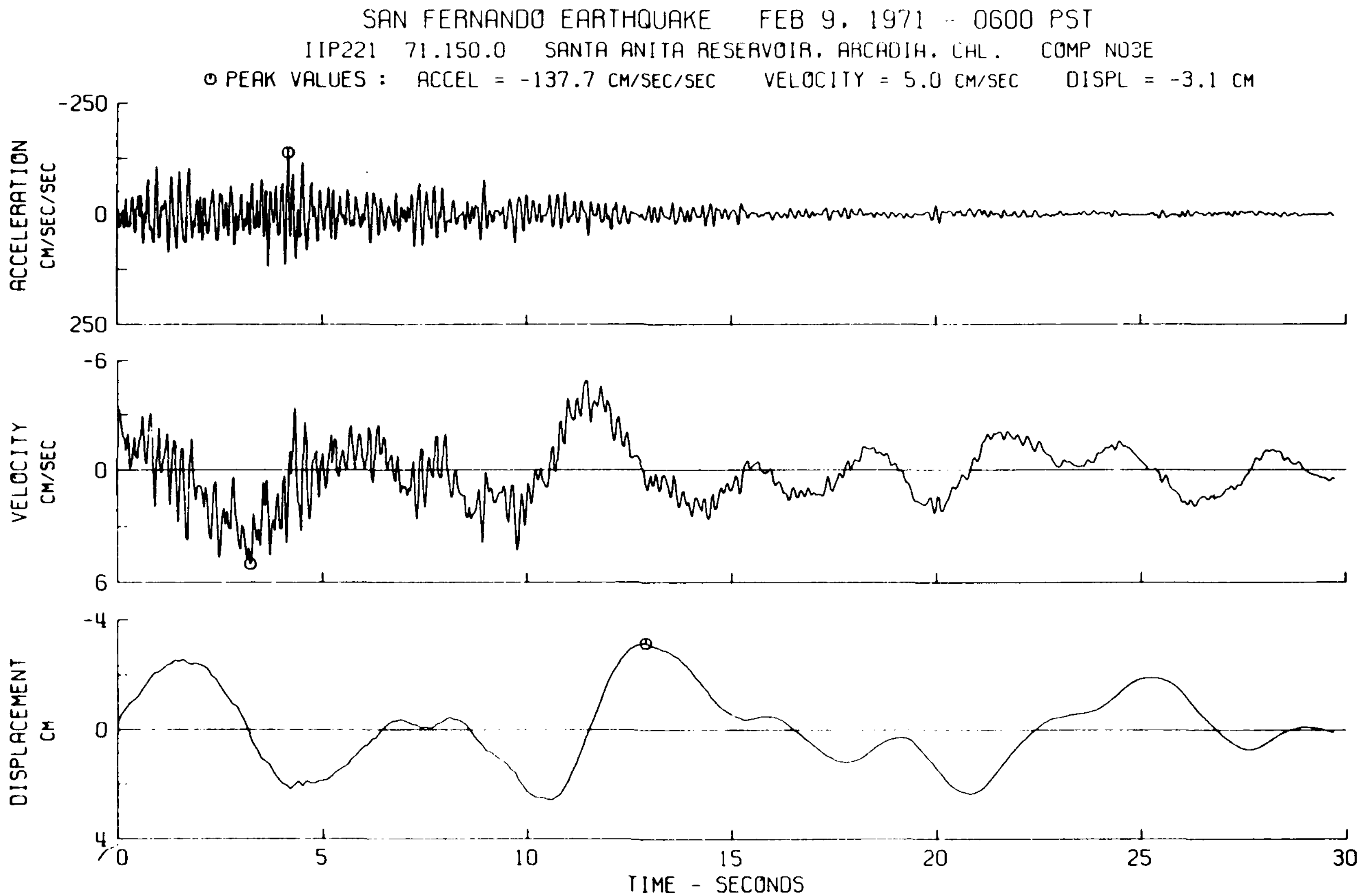
RESPONSE SPECTRUM

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIIG106 71.018.0 CALTECH SEISMOLOGICAL LAB., PASADENA, CAL. COMP S90W

DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL



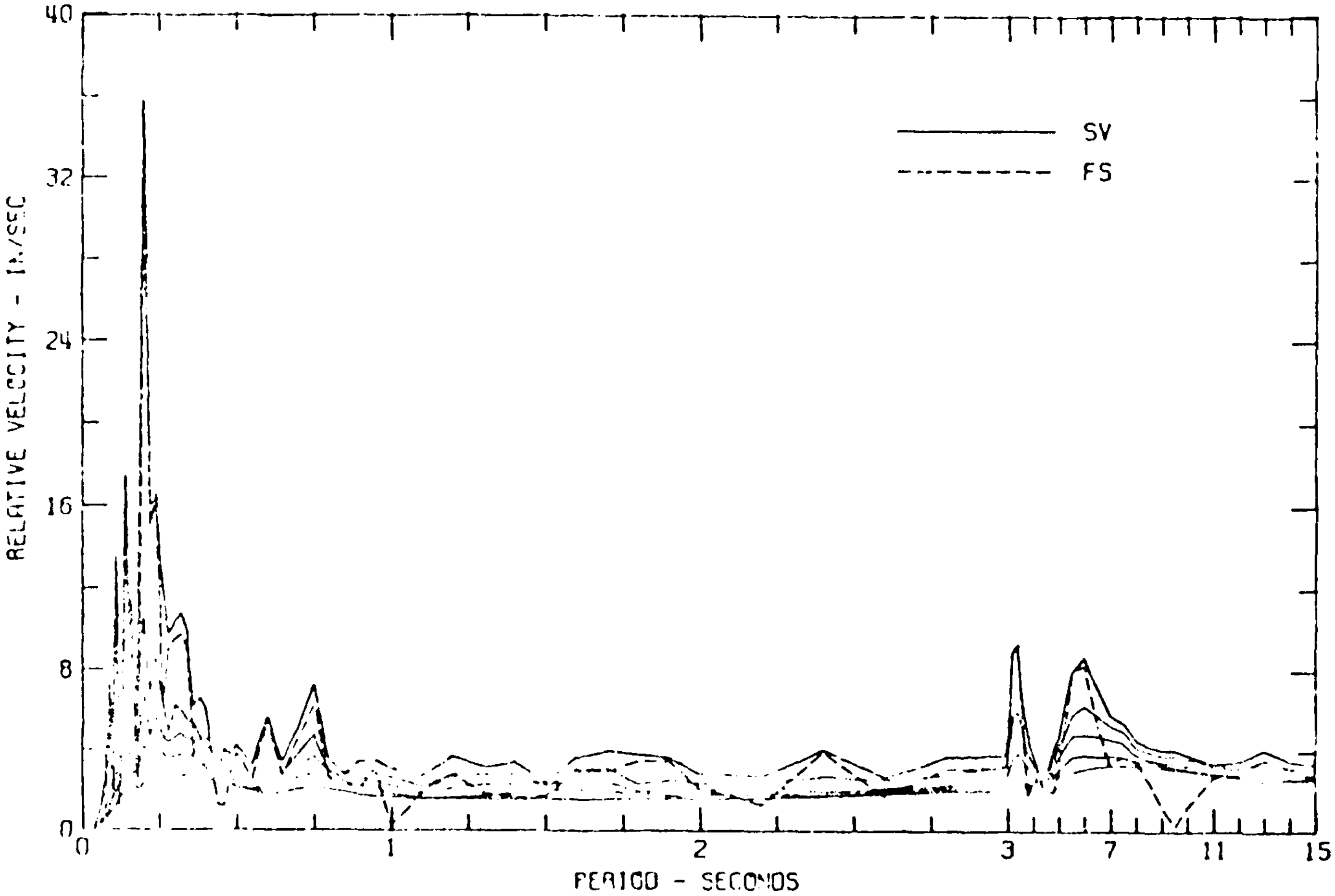

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST
IIP221 71.150.0 SANTA ANITA RESERVOIR, ARCADIA, CHL. COMP N03E
⊙ PEAK VALUES : ACCEL = -137.7 CM/SEC/SEC VELOCITY = 5.0 CM/SEC DISPL = -3.1 CM
ACCELERATION CM/SEC/SEC
-250
0
250
VELOCITY CM/SEC
-6
0
6
DISPLACEMENT CM
-4
0
4
0
5
10
15
20
25
30
TIME - SECONDS

RELATIVE VELOCITY RESPONSE SPECTRUM

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIIP221 71.150.0 SANTA ANITA RESERVOIR, ARCADIA, CAL. COMP N03E

DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL



RESPONSE SPECTRUM

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIIP221 71.150.0 SANTA ANITA RESERVOIR, ARCADIA, CAL. COMP N03E

DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL